Communications Research Centre

HF COMMUNICATIONS PERFORMANCE EVALUATION PROGRAM (U)

by

K. H. Wu
(Directorate of Radio Communications Technologies)
(DGRC/DRL)

CRC REPORT NO. 1436

April 1990
Ottawa

This work was developed under a task sponsored by the Directorate of Maritime Combat Systems (DMCS-6) of the Department of National Defence

Government of Canada
Department of Communications

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Canada

COMMUNICATIONS RESEARCH CENTRE

DEPARTMENT OF COMMUNICATIONS
CANADA

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HF Communications Performance Evaluation Program

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ABSTRACT

This report describes a computer software package that was developed for predicting the error rate of a general HF communication system in a noisy and hostile environment. The original software was designed to facilitate the establishment of a new STANAG (Standard NATO Agreement) for radio communications in the HF band. The program estimates the bit error rate for a variety of system configurations, operational parameters, jammer characteristics and ground wave propagation media, as selected by the user. Sky wave propagation is not considered. This package includes M–FSK and PSK ($M = 2, 4, 8$) signals, CCIR background noise and measured European interference environments. Frequency hopping can be used by the transmitter to evade jamming. The jammer may, in turn, use either follower or partial–band jamming signals to counter the evasion. Estimation of error rate is based on analytical solutions rather than simulations. The cases for M–ary FSK with noise/tone jamming, and 8–ary PSK with tone jamming were analyzed and closed–form solutions were obtained. The program was made flexible enough to allow one to predict and compare the performances of existing and proposed HF communication systems for a variety of operational environments.

Programme d'évaluation de la performance des systèmes de radiocommunications HF

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SOMMAIRE

Le présent rapport décrit un progiciel créé pour prédire le taux d'erreurs des systèmes de radiocommunications HF dans un environnement bruyant et hostile. Le logiciel initial a été conçu pour faciliter l'élaboration d'un nouveau STANAG (accord de normalisation de l'OTAN) sur les radiocommunications dans la bande HF. Le programme permet de prédire le taux d'erreurs sur les bits pour une gamme de configurations de système, de paramètres opérationnels, de caractéristiques des systèmes de brouillage et de modes de propagation de l'onde de sol, selon le choix de l'utilisateur. La propagation par ondes ionosphériques n'est pas considérée. Le progiciel tient compte des signaux de forme MDF (modulation par déplacement de fréquence) à plusieurs niveaux et de forme MDP (modulation par déplacement de phase) ($M = 2, 4, 8$), du bruit ambiant, selon les normes du CCIR, et du brouillage mesuré dans les environnements européens. L'émetteur peut utiliser la technique du saut de fréquence pour éviter le brouillage intentionnel. En contrepartie, pour neutraliser cette évasion, le système de brouillage peut soit suivre les sauts de fréquence, soit utiliser le brouillage sur bande partielle. L'estimation du taux d'erreurs est fondée sur des solutions analytiques plutôt que sur la simulation par ordinateur. Dans le cas des signaux MDF à niveaux multiples avec brouillage par bruit ou par fréquence unique et des signaux MDP à 8 niveaux avec brouillage par fréquence unique, des solutions analytiques complètes ont été obtenues. Le programme est assez souple pour permettre de prédire et de comparer les performances des systèmes de radiocommunications HF, actuels et proposés, dans différents environnements opérationnels.

EXECUTIVE SUMMARY

This report describes a computer software package that was developed for predicting the error rate of a general HF communication system in a noisy and hostile environment. The original software was designed to facilitate the establishment a new STANAG (Standard NATO Agreement) for radio communications in the HF band. The program developed estimates the bit error rate for a variety of system configurations, operational parameters, jammer characteristics and propagation media, as selected by the user. This package includes frequency shift keying (FSK), M–ary phase shift keying (PSK) (M = 2, 4, 8) signals, CCIR background noise and measured European interference environments. Frequency hopping can be used by the transmitter to evade jamming. The jammer may, in turn, use either follower or partial–band jamming signals to counter the evasion. The program was made flexible enough to allow one to predict and compare the performances of a wide range of existing and proposed HF communication systems for a variety of operational environments.

To run the program, the user needs to go through a dialogue to enter the necessary parameters. The program dialogue is kept simple and user–friendly so that it can be used by both technical and military personnel. There are approximately twenty parameters that need to be entered, including functional and numerical entries. The final results are expressed in bit error rate and can be displayed graphically.

The program allows the user to select one of the nine transmitter–related parameters to have multiple values; all other parameters will have only single values. This feature allows the user to view the effect of changes in a specific parameter on the overall system performance.

The program was written in Fortran. An accompanying diskette containing the source and executable codes in the IBM PC format is attached to paper copy version of this report. Distribution of the program is unlimited†.

† The program is also available from the author. Requests can be sent to:
K. H. Wu, Communications Research Centre, P.O.Box 11490, Station H, Ottawa, Ontario, Canada K2H 8S2.

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1 Introduction

A computer software package for predicting performance of an HF digital communication system has been built. The original software was designed to facilitate the establishment of a new STANAG (Standard NATO Agreement) for radio communications in the HF band. The software estimates the bit error rate for a set of system configurations, operational parameters, jammer characteristics and propagation media, as selected by the user. Estimation of error rate is based on analytical solutions rather than simulations.

The software computes the bit error rate based on a set of user input parameters. The program consists of the following components:

1.1 Propagation

The program computes the signal strength for ground wave over a distance for a specified frequency and terrain type. The computation applies to both the desired signal and the jammer signals.

1.2 Interference and Noise

These refer to *unintentional* interference. Intentional interference is referred to as jamming and will be discussed latter. Interference may include signals from other users occupying the same frequency band, which we call occupancy interference, as well as environmental and man–made noise. Alternatively, man–made noise alone can be selected. Man–made noise is noise generated from non–communications sources. This assumes that no other–user signals exist in the frequency band and environmental noise is negligible. The occupancy interference data include statistical variations of the mean power between channels, whereas man–made noise data do not. Therefore, occupancy interference is more representative of that of a real operational environment, especially for a frequency hopping system. The interference statistics vary from season to season, and during the hours of a day. In the program, the user can select either man–made noise or occupancy interference.

1.3 Modulation

Two modulation techniques are included, namely, frequency–shift keying and phase–shift keying. These are the modulations commonly used in the HF band. For FSK, binary and *M*–ary FSK can be selected, whereas for PSK, binary (BPSK), quadrature (QPSK), and 8–ary (8PSK) PSK can be selected.

1.4 Frequency Hopping

The transmitted signal can hop from one frequency channel to another in the neighbourhood of the specified transmitter frequency in order to evade jamming. The program assumes that the propagation characteristics are the same for all hop frequencies.

1.5 Jammer

Two types of jammers may be used, namely, noise and tone jammers. A noise jammer is assumed to contain Gaussian noise over the tone bandwidth of the receiver and is added to the unintentional interference signals to increase the noise level. A tone jammer is a CW signal which interferes with the desired signal.

There are two ways of jamming, namely, follower and partial band jamming. In follower jamming, the jammer attempts to follow the hopping frequency of the transmitter and emits either a noise or tone jamming signal. The effectiveness of the jammer depends on how closely the jammer can follow the hopping frequency. In partial band jamming, the jammer emits simultaneous multiple jamming signals on some of the channels used by a frequency hopping transmitter. For FSK with frequency hopping, at most one of the FSK tones in each channel may be jammed. This requires that the jammer has some knowledge of the frequency bands used by the transmitter.

1.6 Error Correcting Code

Block coding can be used to reduce the symbol error rate when the symbol error rate is moderately high.

2 Propagation

The ground wave propagation curves given in the CCIR report [1] are used to calculate the field strength of the transmitted signal and jammer. Sky wave is not considered in the present software. Five types of terrain can be selected, namely, sea water (sea state 0), wet ground, land, medium dry ground and very dry ground. The propagation curves are reproduced here in Figures 1 – 5. The field strength curves give the field strength E in dBμV/m for a Hertzian vertical electric dipole with a dipole moment $5\lambda/2\pi$ ampere metres, giving a field of 0.3 V/m at a distance of 1 km on the surface of a perfectly conducting plane. (This is equivalent to a 1 kW isotropic radiator). Denote this reference by e_r (in V/m). Then the signal power received by an antenna from a transmitter providing t kW of power into an antenna of gain g_t relative to the reference is

$$p_r = \left[\frac{e_r^2}{Z_0} t\right] \left[\frac{\lambda^2}{4\pi}\right] g_t \qquad (1)$$

where Z_0 ($= 120\pi$) is the impedance of free space. The term in the first parentheses denotes the power received per unit area. The term in the second parentheses denotes

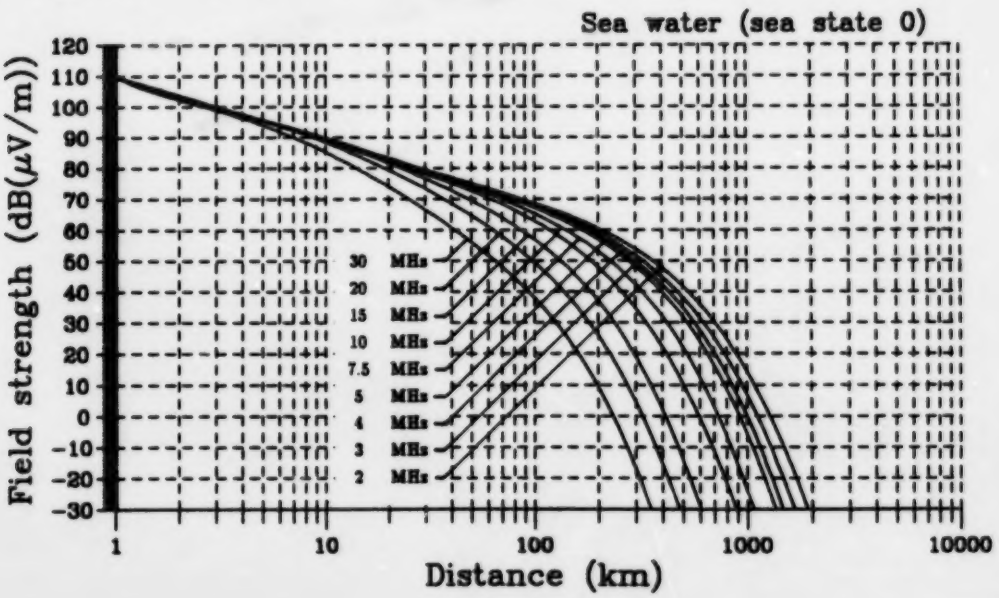


Figure 1 Ground–wave propagation curves for sea water at sea state 0 [1].

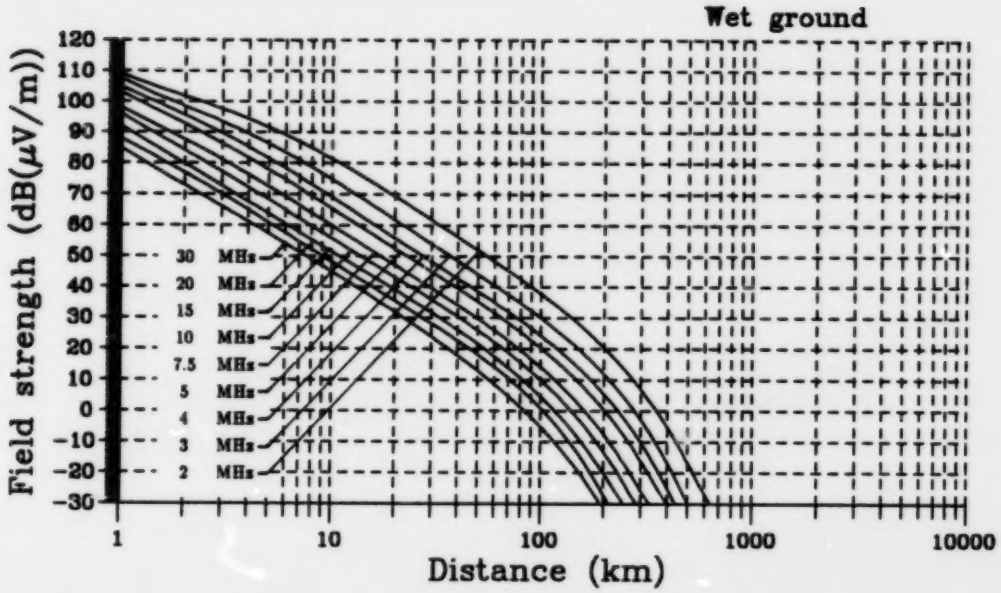


Figure 2 Ground–wave propagation curves for wet ground [1].

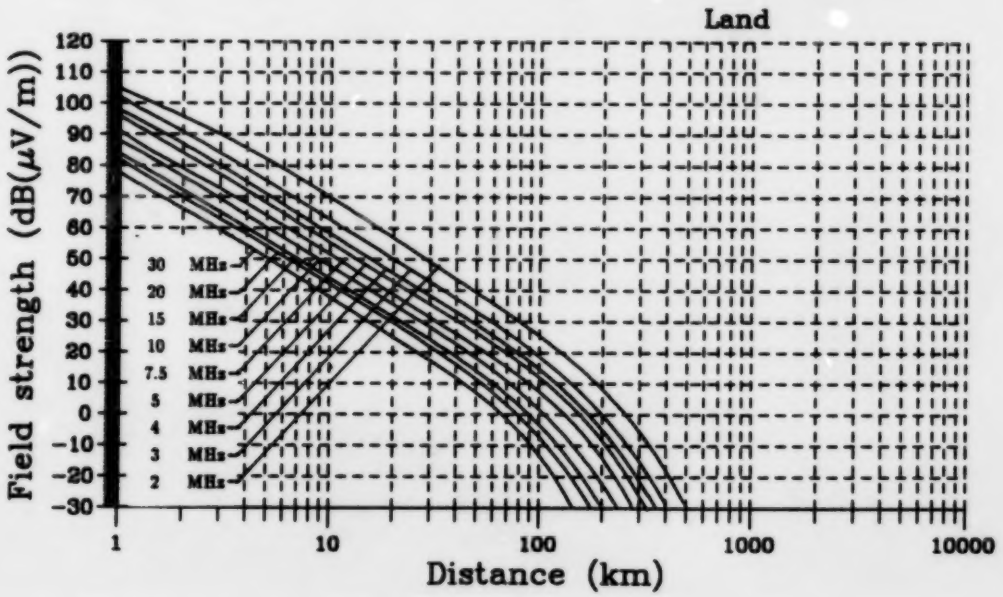


Figure 3 Ground–wave propagation curves for land [1].

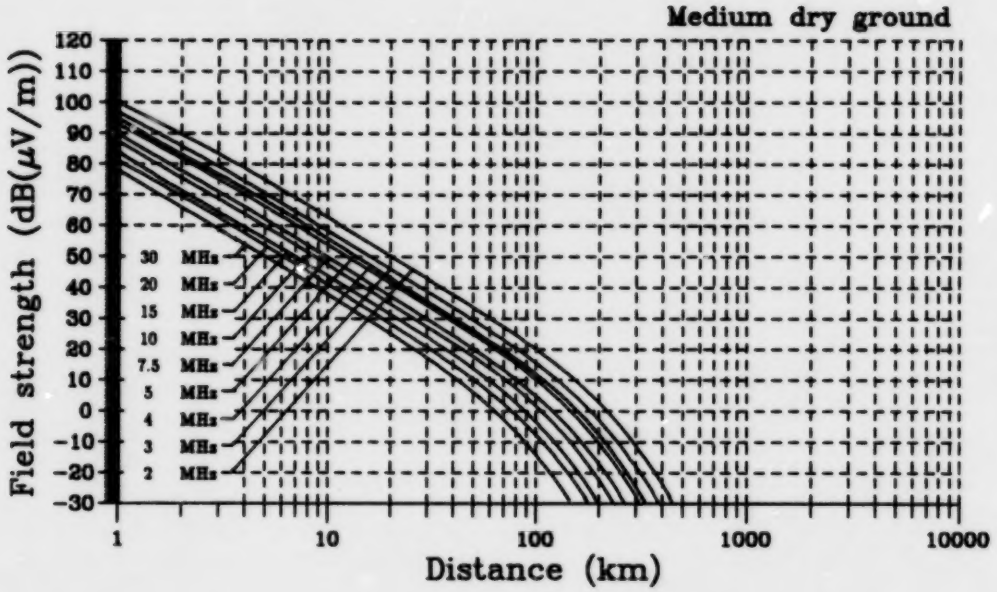


Figure 4 Ground–wave propagation curves for medium dry ground [1].

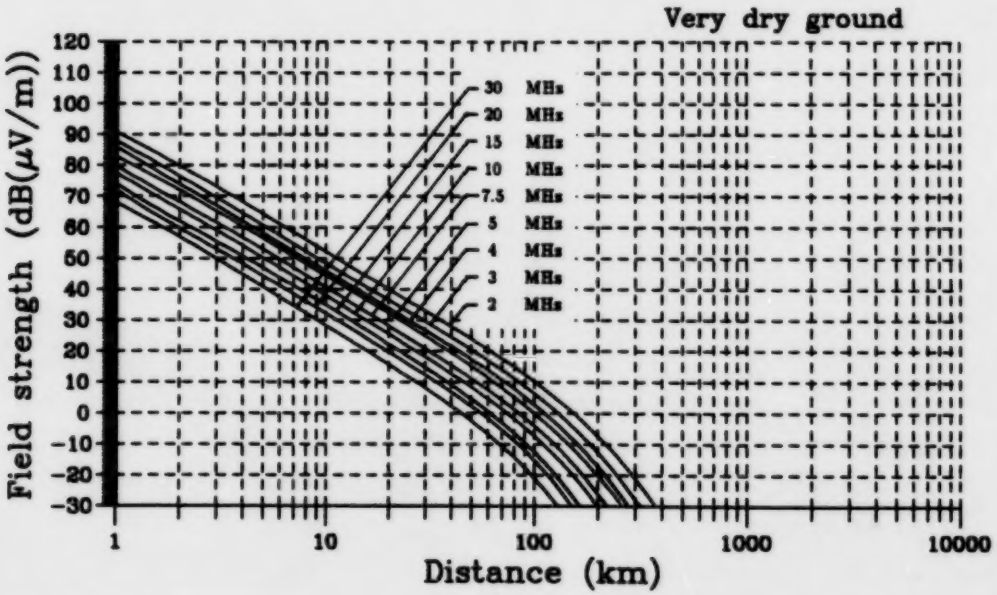


Figure 5 Ground–wave propagation curves for very dry ground [1].

the effective aperture area of a receiving antenna of unity gain. Expressing the above equation in dB (upper–case variables are in dB), we have

$$P_r = E_r - 20 \log_{10} f_m - 107 + T + G_t \qquad (2)$$

where E_r is the field strength in dBμV/m and is the value on the vertical axes in Figures $1-5$, P_r is the antenna output power in dBW, f_m is the frequency in MHz, T is the transmit antenna input power in dBkW, and G_t is the transmit antenna gain in dB.

The propagation curves were generated originally from the GRWAVE program [1]. The algorithm used in the program is rather complicated. To simplify the computation, the curves in Figures $1-5$ are curve–fitted using a fifth–order polynomial equation. The polynomial coefficients are collected in Appendix A. For field strength lower than -30 dBμV/m, extrapolation from the curves may yield inaccurate values. A warning message will be issued if the extrapolated field strength falls below -40 dBμV/m.

3 Interference and Noise

In the absence of other operating transmitters, the dominant noise source in winter is man–made noise. The noise arises chiefly from electric motors, neon signs, power lines and ignition systems located within a few hundred metres of the receiving antenna [2]. The noise level is highest in business areas, medium in residential areas and lowest in rural areas. The noise level decreases with increasing frequency. The dependence of antenna noise figure on frequency is shown in Figure 6. For summer evenings and for frequencies lower than 10 MHz, atmospheric noise dominates. Atmospheric noise is produced mostly by lightning discharges in thunderstorms. It is impulsive in nature and therefore cannot be modelled as Gaussian noise. Performances in impulsive noise are difficult to estimate. In the present program, atmospheric noise is not included. The program is therefore applicable to winter months when the occurrences of thunderstorms are infrequent, or to summer situations when interference or jamming dominates.

An HF channel is usually highly congested because HF signals propagate over very great distances and there are a large number of users. Interference from other users

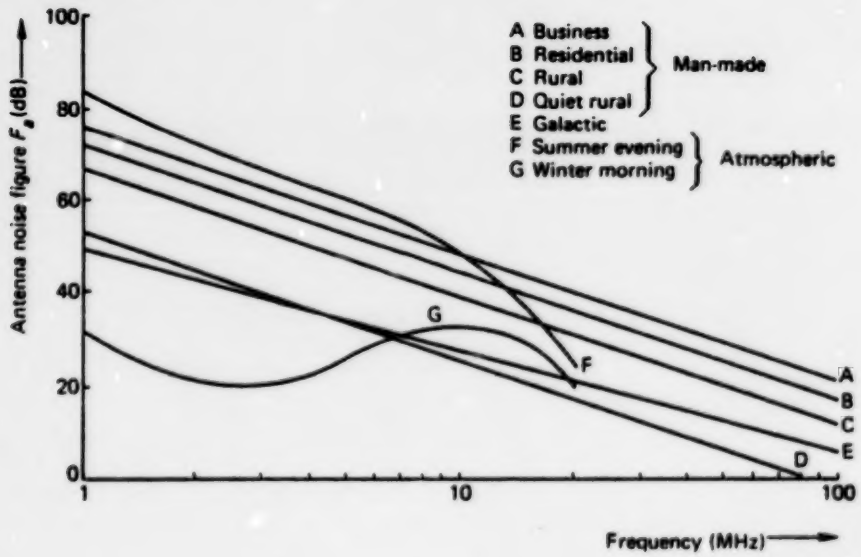


Figure 6 Antenna noise figure dependence upon frequency [2].

may increase the error rate. In the present program, it is assumed that there is a sufficient number of interferers in an occupied channel that the overall interference signal can be assumed to be Gaussian noise–like. This assumption is mostly due to lack of knowledge of the signal statistics in a specific environment and for mathematical convenience. In a frequency hopping system, the signal may hop into a channel which is being occupied by distant transmitters. Occupancy statistics are required to characterize the interference probability distribution between channels and hence to calculate the error probability.

In the present program, the user can select either man–made noise [2] or occupancy interference [3]. In both cases, Gaussian noise is assumed.

3.1 Man–Made Noise

The noise figures for man–made noise and atmospheric noise are shown in Figure 6. Only man–made noise is considered here. The noise figures for business, residential and rural areas are given respectively by

$$F_{\text{bus}} = 76 - 27.7 \log_{10} f_{\text{m}}$$
$$F_{\text{res}} = 72 - 27.7 \log_{10} f_{\text{m}} \qquad (3)$$

$$F_{rur} = 67 - 27.7 \log_{10} f_m$$

where $F_{...}$ is in dB and f_m is the frequency in MHz. The noise power in dBW is given by

$$P_n = F_{...} + B - 204 \tag{4}$$

where B is the noise equivalent bandwidth in dBHz.

3.2 Occupancy Interference

The interference statistics due to regular users occupying a channel is based on the data given in [3]. These data are representative of the very congested European environment. Occupancy is defined as the probability that the signal power level, I, exceeds a threshold level of z, i.e. $P(I>z)$. The measured occupancy data given in [3] are grouped in four categories, namely, summer day, summer night, winter day and winter night. The data set in each category is subdivided into five frequency bands, viz. 1.5 – 2.99 MHz, 3 – 5.99 MHz, 6 – 11.99 MHz, 12 – 20.99 MHz and 21 – 30 MHz. The selection of these frequency bands is arbitrary. The occupancy data in each band are averaged. Channels associated with aeromobile, broadcast, and amateur are excluded because of their sensitivity or regular heavy usage, i.e. it is assumed that these channels are not used in the present application. The occupancy curves are plotted in Figures 7 – 10, with cumulative occupancy in percentage versus signal power in dBm. The power level was measured through a receiver bandwidth of 1 KHz. The dotted lines on the right of the curves are extrapolations from the curves to zero occupancy. The dotted lines on the left go straight to the 100% occupancy level at the –119 dBm signal power level. This assumes that the noise floor is at –119 dBm. This is a worst case guess since the actual noise floor level is not given in [3].

The signal power was measured by using a receiver with a bandwidth of 1 KHz. For a receiver with a bandwidth B, the equivalent occupancy is given by [4]

$$P_B \cong 1 - \left[1 - P_{B_0}\right]^{\frac{B}{B_0}} \tag{5}$$

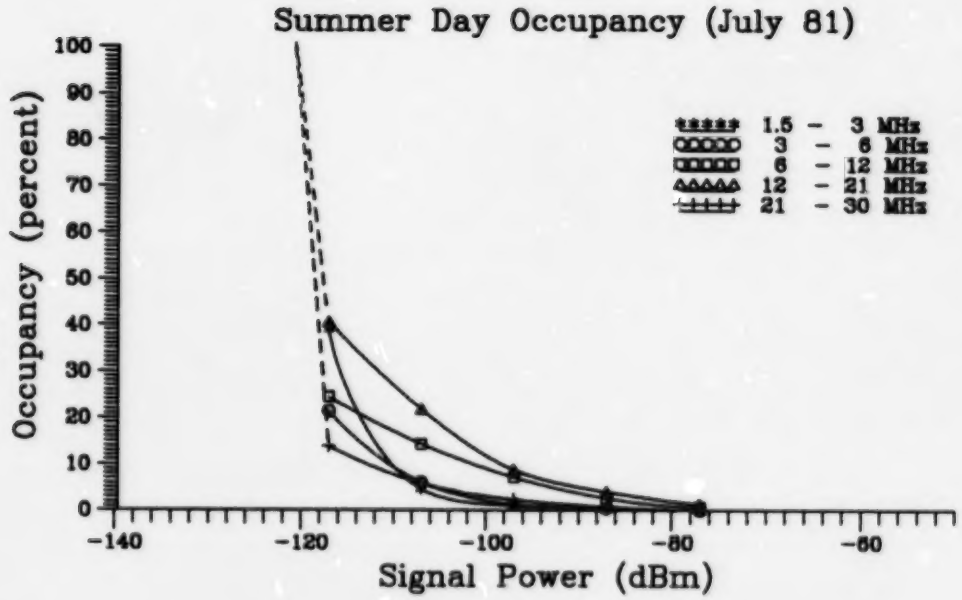


Figure 7 Occupancy statistics for summer day.

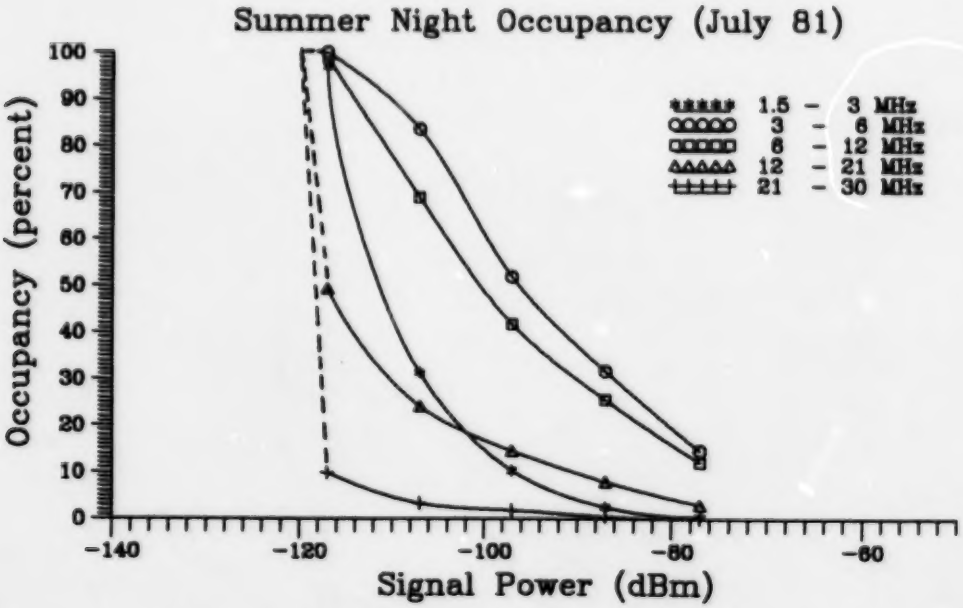


Figure 8 Occupancy statistics for summer night.

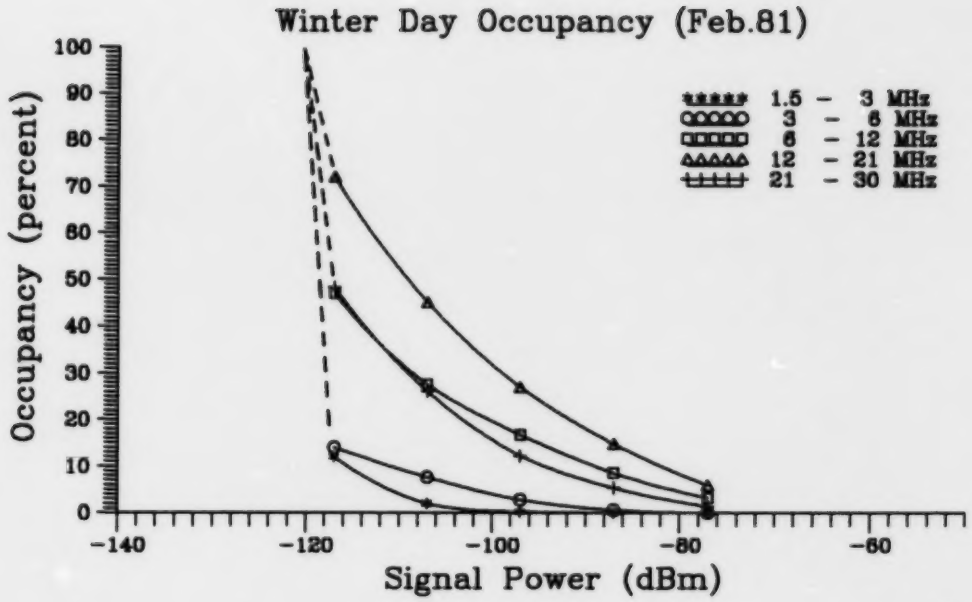


Figure 9 Occupancy statistics for winter day.

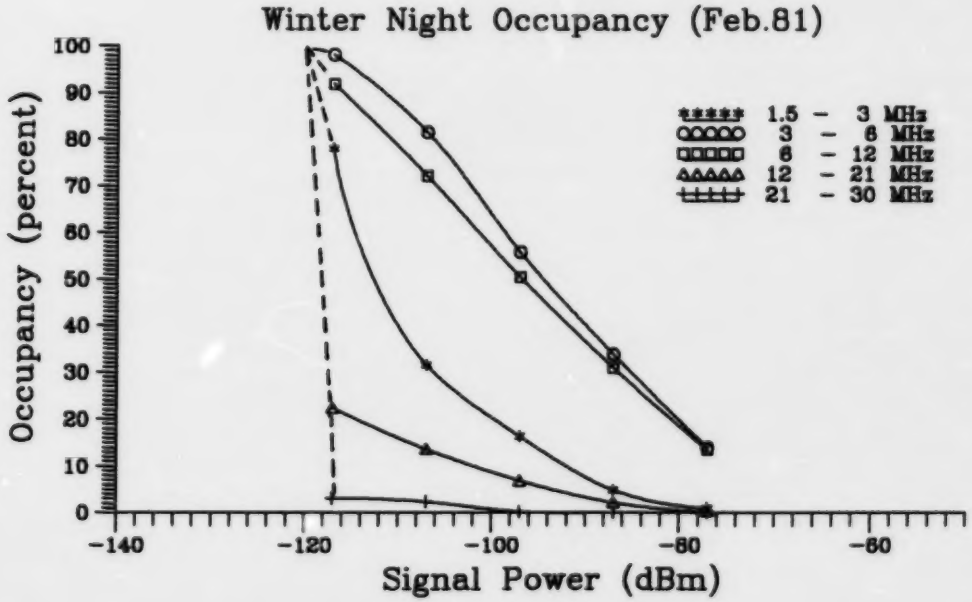


Figure 10 Occupancy statistics for winter night.

where $P_{B'}$, P_{B_0} are the occupancy cumulative probability with receiver bandwidths B and B_0 (= 1 KHz), respectively. Eq.(5) assumes that the occupancy probability due to change in bandwidth to B is equivalent to the combinational probability of (B/B_0) *discrete* channels.

Occupancy values at signal power levels of –119, –117, –115, ..., –55 dBm are sampled from the curves in a step increment of 2 dB. Each value is then adjusted for the receiver bandwidth using (5). A histogram can be derived from the cumulative occupancy curves by taking the difference between adjacent data, i.e.

$$\begin{aligned} P(-119 < I < -117) &= P(I > -119) - P(I > -117) \\ P(-117 < I < -115) &= P(I > -117) - P(I > -115) \\ &\vdots \\ P(-57 < I < -55) &= P(I > -57) - P(I > -55) \end{aligned} \tag{6}$$

The resultant symbol error rate is the weighted average of the symbol error rates at the I steps, viz.

$$\begin{aligned} P_{sr} = {} & P_s(I{=}-118) \times P(-119 < I < -117) + P_s(I{=}-116) \times P(-117 < I < -115) \\ & + \ldots + P_s(I{=}-56) \times P(-57 < I < -55) \end{aligned} \tag{7}$$

where $P_s(I{=}x)$ denotes the symbol error rate at an interference level equal to x dBm.

To calculate the symbol error rate $P_s(I{=}x)$, the interference level x (dBm) is converted to the field strength in the air (i.e. by taking out the characteristics of the antenna used in the interference measurements [3]). A frequency independent active antenna was used. The conversion equation is given by

$$\begin{aligned} 20 \log_{10} e_s &\cong I\,(\text{dBm}) + 112.8 \\ E_s &\cong I\,(\text{dBm}) + 112.8 \end{aligned} \tag{8}$$

where e_s, E_s are the field strength in μV/m and dBμV/m respectively.

Assuming a dipole antenna is used for receiving, the output power from the receiving antenna, P_i in dBW, is

$$P_i = E_s - 20 \log_{10} f_m - 107 + G_i \tag{9}$$

where f_m is the frequency in MHz, and G_i is the antenna gain for the interference. Substituting (8) into (9), we have

$$P_i \cong I - 20 \log_{10} f_m + G_i + 5.8 \tag{10}$$

This interference power value is input to the symbol error equations to be described in Section 5.

4 Jamming

Two types of jamming can be selected, namely, noise and tone jamming. Noise jamming consists of Gaussian noise spread over the bandwidth of the receiver. The jamming noise is added with the interference power calculated as described in Section 4. Tone jamming consists of a single CW tone located within the passband of the receiver. In both cases, the jamming is attenuated by the propagation loss as described in Section 3. The propagation medium of the jamming can be different from that of the communications signal.

5 Modulations and Symbol Error Rate

Frequency and phase shift keying are included in the present program. The modulation schemes include binary FSK and M–ary FSK (MFSK) as well as binary, quadrature and 8–ary PSK.

The noise power, either intentional or unintentional, is calculated based on the noise–equivalent bandwidth, B. The noise–equivalent bandwidth is defined as equal to the symbol rate (in number of symbols/sec.), which is also equal to the tone bandwidth. The user is required to specify the value of the tone bandwidth. The value of tone bandwidth is used in Eq.(4) in a man–made noise case or in Eq.(5) in an occupancy–interference case.

Known equations for prediction of error rate are quoted below with their sources of reference. Equations for MFSK and 8–ary PSK with a tone jammer were not found in the open literature. These cases were derived and their derivations are given in Appendices B and C.

5.1 Binary FSK

BFSK with and without frequency hopping can be selected in the program. In the case of FSK without frequency hopping, tone jamming or noise jamming or both can be chosen for the mark and space channels. Regardless of the combinations of jamming selected, the total jamming power is equally split among the jammed channels. In the case of BFSK with frequency hopping, either the mark or space channel can be jammed, but not both. Also, the user must select either noise or tone jamming.

5.1.1 BFSK without jammer

For BFSK without a jammer, the symbol error probability is given by (p.307, [7])

$$P_s = \frac{1}{2} \exp\left[-\frac{S}{2N_t}\right] \tag{11}$$

where S is the signal power,
N_t is the interference or noise power.

5.1.2 BFSK with noise jammers

For noise–only jamming (i.e. no tone jamming), the symbol error probability is given by (p.17, [5])

$$P_s = \frac{1}{2} \exp\left[-\frac{S}{2N_t+N_{i1}+N_{i2}}\right] \tag{12}$$

where S is the signal power,
N_t is the interference or noise power,
N_{i1} is the jammer power in channel 1,
N_{i2} is the jammer power in channel 2.

5.1.3 BFSK with tone jammers in both mark and space channels

For tone–jamming in both mark and space channels and without noise jamming, the symbol error probability is given by (p.17, [5])

$$P_{s2} = \frac{1}{2\pi}\int_0^{2\pi}\left\{Q\left[\sqrt{\frac{J}{N_t}},\frac{D(x)}{\sqrt{2N_t}}\right] - \frac{1}{2}\exp\left[-\frac{2J+D^2(x)}{4N_t}\right] I_0\left[\frac{\sqrt{2}JD(x)}{2N_t}\right]\right\} dx \tag{13}$$

where

$$D^2(x) = 2S + 2J + 4\sqrt{SJ}\cos x$$

J is the jamming power in one sub–channel and $I_0(z)$ is the modified Bessel function of zero order. I_0 increases rapidly with z and can easily overflow the computation. For $z >$ 10, an asymptotic approximation for $I_0(z)$ is

$$I_0(z) \cong \frac{e^z}{\sqrt{2\pi z}} \tag{14}$$

Substituting (14) into (13), we have

$$P_2 \cong \frac{1}{2\pi}\int_0^{2\pi}\left\{Q\left[\sqrt{\frac{J}{N_t}},\frac{D(x)}{\sqrt{2N_t}}\right] - \frac{1}{2\sqrt{2\pi D(x)}}\exp\left[-\frac{[\sqrt{2J}-D(x)]^2}{4N_t}\right]\right\} dx,$$

$$\text{for } \frac{\sqrt{2}JD(x)}{2N_t} > 10 \tag{15}$$

The function $Q(.,.)$ is the Marcum Q–function and is defined as

$$Q(\alpha,\beta) = \int_\beta^\infty x\exp\left[-\frac{x^2+\alpha^2}{2}\right] I_0(\alpha x)\, dx \tag{16}$$

To facilitate computation, the following conditions are used

$$Q(\alpha,\beta) = \begin{cases} \exp\left[-\frac{\beta^2}{2}\right], & \alpha = 0 \\ \frac{1}{2\pi}\int_{\beta}^{\infty} \sqrt{x}\exp\left[-\frac{(x-\alpha)^2}{2}\right] dx, & \alpha\beta > 4 \\ \int_{\beta}^{\infty} x\exp\left[-\frac{x^2+\alpha^2}{2}\right] I_0(\alpha x)\, dx, & \text{otherwise} \end{cases} \quad (17)$$

5.1.4 BFSK with tone jammers in either mark or space channel

For tone–jamming in only one channel and without noise jamming, the error rate is given by (p.18, [5])

$$P_1 = \frac{1}{2} Q\left(\sqrt{\frac{J}{N_t}}, \sqrt{\frac{S}{N_t}}\right) \quad (18)$$

5.1.5 BFSK with tone and noise jammers in both mark and space channels

The general case with interferences and noise in both channels is given by (p.16,[5])

$$P_e = \frac{1}{4\pi}\int_0^{2\pi} \left\{ Q\left[\frac{B_2}{\sqrt{N_1+N_2}}, \frac{D_1(x)}{\sqrt{N_1+N_2}}\right] + Q\left[\frac{B_1}{\sqrt{N_1+N_2}}, \frac{D_2(x)}{\sqrt{N_1+N_2}}\right] - \frac{N_1}{N_1+N_2}\exp\left[-\frac{B_2^2+D_1^2(x)}{2(N_1+N_2)}\right] I_0\left[\frac{B_2 D_1(x)}{N_1+N_2}\right] - \frac{N_2}{N_1+N_2}\exp\left[-\frac{B_1^2+D_2^2(x)}{2(N_1+N_2)}\right] I_0\left[\frac{B_1 D_2(x)}{N_1+N_2}\right] \right\} dx \quad (19)$$

where

$$D_j^2(x) = 2S + 2J_j + 4\sqrt{SJ_j}\cos x$$

and

$B_1 = \sqrt{2J_1}$, J_1 is the jamming power in channel 1,

$B_2 = \sqrt{2J_2}$, J_2 is the jamming power in channel 2.

For large arguments in $I_0(.)$, the approximation in (14) can be used to prevent overflowing,

$$P_e = \frac{1}{4\pi}\int_0^{2\pi}\left\{ Q\left[\frac{B_2}{\sqrt{N_1+N_2}}, \frac{D_1(x)}{\sqrt{N_1+N_2}}\right] + Q\left[\frac{B_1}{\sqrt{N_1+N_2}}, \frac{D_2(x)}{\sqrt{N_1+N_2}}\right] - \frac{N_1}{N_1+N_2}\sqrt{\frac{N_1+N_2}{2\pi B_2 D_1(x)}}\exp\left[-\frac{[B_2-D_1(x)]^2}{2(N_1+N_2)}\right] - \frac{N_2}{N_1+N_2}\sqrt{\frac{N_1+N_2}{2\pi B_1 D_2(x)}}\exp\left[-\frac{[B_1-D_2(x)]^2}{2(N_1+N_2)}\right]\right\} dx \qquad (20)$$

5.2 *M*–ary FSK

In the case FSK with frequency hopping, we assume that *at most one jammer* is used to jam each of the M channels. This is an optimal condition for the jammer in a frequency hopping scheme. The jammer may fall into the transmission sub–channel or one of the M–1 complementary sub–channels. The symbol errors are given in the following. Details of the derivations are given in Appendix B.

5.2.1 *M*–ary FSK without a jammer

The symbol error rate without a jammer is given by

$$P_{s3} = \frac{1}{M}\sum_{i=2}^{M}(-1)^i\binom{M}{i}\exp\left[-\frac{A^2}{2N}\left[1-\frac{1}{i}\right]\right] \qquad (21)$$

where

N_t is the unintentional noise power,

A is the signal amplitude, $= \sqrt{2S}$, where S is the signal power.

5.2.2 *M*–ary FSK with a tone jammer

The symbol error rate for a tone–jammed system is given by

$$P_{s_J} = \frac{1}{M} P_{s1} + \frac{M-1}{M} P_{s2} \tag{22}$$

where

$$P_{s1} = \begin{cases} \frac{1}{M} \sum_{i=2}^{M} (-1)^i \binom{M}{i} \exp\left[-\frac{A^2+B^2}{2N_t}\left[1-\frac{1}{i}\right]\right] I_0\left[\frac{AB}{N_t}\left[1-\frac{1}{i}\right]\right], & \frac{AB}{N_t}\left[1-\frac{1}{i}\right] < 10 \\ \frac{1}{M}\sqrt{\frac{N_t}{2\pi AB}} \sum_{i=2}^{M} (-1)^i \binom{M}{i} \exp\left[-\frac{(A-B)^2}{2N_t}\left[1-\frac{1}{i}\right]\right]\left[1-\frac{1}{i}\right]^{-\frac{1}{2}}, & \frac{AB}{N_t}\left[1-\frac{1}{i}\right] > 10 \end{cases} \tag{22a}$$

and

$$P_{s2} = \frac{1}{M-1} \sum_{i=2}^{M-1} (-1)^i \binom{M-1}{i} \exp\left[-\frac{A^2}{2N_t}\left[1-\frac{1}{i}\right]\right]$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} \exp\left[-\frac{A^2}{2N_t(j+1)}\right] \cdot$$

$$\left\{ Q(v_2, v_1) - \frac{1}{j+2} \exp\left[-\frac{\frac{A^2}{N_t(j+2)} + \frac{B^2}{N_t}(j+1)}{2(j+1)}\right] I_0\left[\frac{AB}{N_t(j+2)}\right] \right\} \tag{22b}$$

where

N_t is the unintentional noise power,

A is the signal amplitude, $= \sqrt{2S}$, where S is the signal power,

B is the tone jammer amplitude, $= \sqrt{2J}$, where J is the tone jamming power,

$D^2 = A^2 + B^2 + 2AB \cos x$, where x is the phase angle between the signal and tone jammer.

and

$$v_1 = \frac{A}{\sqrt{N_t(j+1)(j+2)}}, \text{ and } v_2 = B\sqrt{\frac{j+1}{N_t(j+2)}} \tag{23}$$

5.2.3 *M*–ary FSK with a noise jammer

The symbol error rate for a noise jammed system is given by

$$P_{s_J} = \frac{1}{M} P_{s1} + \frac{M-1}{M} P_{s2} \tag{24}$$

where

$$P_{s1} = 1 - \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \exp\left[-\frac{jA}{2[N_t + j(N_t+J)]}\right] \frac{1}{1 + \frac{j(N_t+J)}{N_t}} \tag{24a}$$

and

$$P_{s2} = \frac{1}{M-1} \sum_{i=2}^{M-1} (-1)^i \binom{M-1}{i} \exp\left[-\frac{A^2}{2N_t}\left[1 - \frac{1}{i}\right]\right]$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} - \frac{1}{\frac{N_t}{N_t+J} + j+1} \exp\left[-\frac{A^2}{2N_t}\left[\frac{N_t + j(N+J)}{N_t + (j+1)(N_t+J)}\right]\right] \tag{24b}$$

where

N_t is the unintentional noise power,

A is the signal amplitude, $= \sqrt{2S}$, where S is the signal power,

J is the noise jammer power.

5.3 Binary PSK

5.3.1 BPSK without a jammer

For BPSK without a jammer, the symbol error probability is given by

$$P_s = q\left[\sqrt{\frac{2S}{N_t}}\right] \tag{25}$$

where S is the signal power, and q(.) is the normal q–function, which is given by

$$q(y) = \frac{1}{2}\,\mathrm{erfc}\left[\frac{y}{\sqrt{2}}\right] \tag{26}$$

5.3.2 BPSK with a noise jammer

For noise–only jamming without a tone jammer, the symbol error probability is given by

$$P_s = q\left[\sqrt{\frac{2S}{N_t+J}}\right] \tag{27}$$

where S is the signal power, J is the jamming power in a channel.

5.3.3 BPSK with a tone jammer

For tone–only jamming without a noise jammer, the symbol error probability is given by

$$P_s = \frac{1}{2\pi}\int_0^{2\pi} q\left[\sqrt{\frac{2S}{N_t}}\left[1-\sqrt{\frac{2J}{S}}\sin\theta_j\right]\right] d\theta_j \tag{28}$$

5.4 Quadrature PSK

5.4.1 QPSK without a jammer

For QPSK without a jammer, the symbol error probability is given by (p.272, [6])

$$P_s = 2\,q\left[\sqrt{\frac{S}{N_t}}\right] - q^2\left[\sqrt{\frac{S}{N_t}}\right] \tag{29}$$

where S is the signal power.

5.4.2 QPSK with a noise jammer

For noise–only jamming without a tone jammer, the symbol error probability is given by

$$P_s = 2\,q\left[\sqrt{\frac{S}{N_t+J}}\right] - q^2\left[\sqrt{\frac{S}{N_t+J}}\right] \tag{30}$$

where S is the signal power, J is the jamming power in a channel.

5.4.3 QPSK with a tone jammer

For tone–only jamming without a noise jammer, the symbol error probability is given by (p.268–272, [6])

$$P_s = \frac{1}{2\pi}\int_0^{2\pi} P_I(\theta_j) + P_Q(\theta_j) - P_I(\theta_j)\,P_Q(\theta_j)\,d\theta_j \tag{31}$$

where

$$P_I = q\left[\sqrt{\frac{S}{N_t}}\left[1 - \sqrt{\frac{2J}{S}}\sin\theta_j\right]\right] \tag{31a}$$

$$P_Q = q\left[\sqrt{\frac{S}{N_t}}\left[1 + \sqrt{\frac{2J}{S}}\cos\theta_j\right]\right] \tag{31b}$$

5.5 8–ary PSK

5.5.1 8–ary PSK with a tone jammer

The derivation of symbol error rate for 8–ary PSK with a tone jammer is given in Appendix C. The result is given as follows:

For $\frac{A}{2\sqrt{N_t}} < 2$,

$$P_s = 1 - \frac{1}{(2\pi)^2} \int_0^{2\pi} \int_{-\frac{\pi}{8}}^{\frac{\pi}{8}} \exp\left[-\frac{B}{N_t}\right] \left\{1 + \frac{A}{2}\sqrt{\frac{\pi}{N_t}} \exp\left[\frac{A^2}{4N_t}\right] \operatorname{erfc}\left[-\frac{A}{2\sqrt{N_t}}\right]\right\} d\theta \, d\theta_j \tag{32}$$

where

$$A = 2\left[\sqrt{S}\cos\theta + \sqrt{J}\sin(\theta - \theta_j)\right]$$
$$B = S + J - 2\sqrt{SJ}\sin\theta_j$$

the outer two integrals must be evaluated numerically.

For $\frac{A}{2\sqrt{N_t}} > 2$,

$$P_c \cong 1 - \frac{1}{4\pi} \int_0^{2\pi} \left[\operatorname{erf}\left[\frac{0.3827\ (\sqrt{S}\cos\theta_j - \sqrt{J}\sin\theta_j) - 0.9239\ (\sqrt{S}\sin\theta_j + \sqrt{J}\cos\theta_j)}{\sqrt{N_t}}\right] - \operatorname{erf}\left[\frac{-0.3827\ (\sqrt{S}\cos\theta_j - \sqrt{J}\sin\theta_j) - 0.9239\ (\sqrt{S}\sin\theta_j + \sqrt{J}\cos\theta_j)}{\sqrt{N_t}}\right]\right] d\theta_j \tag{33}$$

There is no closed form solution for the last integral. The integration must be evaluated numerically.

5.5.2 8–ary PSK with a noise jammer

The symbol error rate for an 8–ary PSK is given by (p.316, [7])

$$P_s = 1 - \int_{-\frac{\pi}{8}}^{\frac{\pi}{8}} f(\theta)\, d\theta \tag{34}$$

where

$$f(\theta) = \frac{1}{2\pi}\exp\left[-\frac{S}{N_t}\right] + \sqrt{\frac{S}{\pi N_t}}\cos\theta\exp\left[-\frac{S}{N_t}\sin^2\theta\right]\left[1-\frac{1}{2}\operatorname{erfc}\left[\frac{S}{N_t}\cos\theta\right]\right]$$

6 Frequency Hopping and Ways of Jamming

Frequency hopping is a means of evading jamming by switching the transmit frequency of every N–symbol transmission, where N is equal to or greater than unity. There are two ways to jam a hopping signal, namely, follower and partial–band strategies. A follower jammer follows and keeps track of the hopping frequency of the signal. The effectiveness of this approach depends on the processing delay in locating and following the frequency hopping signal. A partial–band jammer spreads its signal power over a selected set of the hop channels used by the transmit signal. The strategy attempts to cause an unacceptable increase in the overall symbol error rate, by causing a large increase in error rate in a fraction of the hop channels.

6.1 Follower Jamming

In follower jamming, the jammer detects the presence of the transmit signal in a channel and attempts to jam the channel by transmitting a tone or noise interference. Path difference as well as the processing time required to detect the presence of the signal constitute a delay in the jamming process, i.e. the portion of the transmission at the beginning of a hop will not be jammed. To ensure the geometry between the transmitter, receiver and jammer is proper, the following identities must be satisfied:

$$\begin{aligned} |d_3 - d_2| &\leq d_1 \\ d_2 + d_3 &\geq d_1 \end{aligned} \tag{35}$$

where d_1, d_2, d_3 are the distances between the receiver and transmitter, transmitter and jammer, receiver and jammer, respectively. The time delay due to path difference is

$$\tau_{pd} = \frac{d_2 + d_3 - d_1}{c} \tag{36}$$

where c is the velocity of propagation ($= 3 \times 10^8$ m/sec.). The total time delay is

$$\tau_t = \tau_{pd} + \tau_{ps} \tag{37}$$

where τ_{ps} is the processing time of the jammer, which includes tuning time and integration time. Assume that N symbols are transmitted at each hop frequency and that slow hop rate is used, i.e. $N > 1$, the number of symbols that escape jamming at the beginning of a hop is

$$N_{nj} = \min\{\tau_t \times R_{sym}, N\} \tag{38}$$

where R_{sym} is the symbol rate in number of symbols transmitted per second. For $N_{nj} = N$, the jammer cannot follow the signal. The number of jammed symbols in each hop is

$$N_j = N - N_{nj} \tag{39}$$

The resultant symbol error probability is then given by

$$P_s = \frac{N_j \; P_s(\text{with jamming}) \; + \; N_{nj} \; P_s(\text{no jamming})}{N} \tag{40}$$

6.2 Partial–Band Jamming

In partial–band jamming, some of the channels used by the transmitter are jammed simultaneously. Let ρ be the fraction of the number of channels that are jammed, the resultant symbol error probability is given by

$$P_s = \rho \; P_s(\text{with jamming}) + (1-\rho) \; P_s(\text{no jamming}) \tag{41}$$

In the case of FSK with frequency hopping, it is assumed that at most one sub–channel in each channel is jammed. The jammed sub–channel can be either the transmission one or the complementary one. By jamming in this manner, the jammer is able to optimize its jamming power by not double jamming a single channel redundantly.

7 Coding

Coding can be used to reduce the symbol error rate. In the present program, the effect of an (n,k) block code is included, where k is the length of information sequence in each block and n is the length of information sequence plus the parity bits in each block. The lower bound for the symbol error rate with block coding can be approximated by (p.42, [5])

$$P_{is} \geq \sum_{i=t+1}^{2t+1} \frac{2t+1}{n} \binom{n}{i} P_s^i (1-P_s)^{n-i} + \sum_{i=2t+1}^{n} \frac{i}{n} \binom{n}{i} P_s^i (1-P_s)^{n-i} \tag{42}$$

where

$t = \frac{n-k}{2}$, the maximum number of errors correctable by a (n,k) block code.

8 Bit Error Rate

For a binary modulation system, the bit error rate is equal to the symbol error rate. For others, bit error rate can be derived or approximated from symbol rate. In an M–ary FSK system, the translation is related by (p.42, [5])

$$P_b = \frac{M}{2(M-1)} P_s \tag{43}$$

where M is the number of different symbols.

In an M–ary PSK system, the translation is approximated by

$$P_b \cong \frac{P_s}{\log_2 M} \tag{44}$$

The approximation assumes that a Gray code is used, in that adjacent codes differ by only one bit. The approximation is good when P_s is low so that errors occur mostly as the adjacent symbols. On the other hand, when the signal to noise/jammer ratio is very low, i.e. high P_s, all symbols will have an equal probability of being randomly selected, and Eq.(43) then becomes more appropriate. At a moderately high symbol error rate,

the actual bit error rate lies somewhere between those given in (43) and (44).

9 Using the Program

The elements described above have been packaged in a computer program which can run in an IBM PC. The program is written in Fortran and compiled using the Microsoft Fortran compiler. The program contains library routines from Numerical Recipes [8], and HGRAPH [9]. The source code of the program is available from the author.

To facilitate comparison for variations in error rates, multiple runs are allowed with multiple inputs in one parameter. The parameters that can be selected for multiple inputs are:

(1) type of ground for the transmitter (5)
(2) distance between the transmitter and receiver (9)
(3) transmitter signal power (9)
(4) transmitter antenna gain (9)
(5) receiver antenna gain for the signal (9)
(6) type of interference (4 for occupancy interference, 3 for man–made noise)
(7) carrier frequency (9)
(8) receiver tone bandwidth (9)
(9) receiver antenna directivity factor for noise (9)

The number in parentheses after each item indicates the maximum number of entries that can be entered. Parameters associated with the jammer do not allow multiple inputs.

Two data files are required to run the program, namely, LOSS.DAT and OCCUPY.DAT. The former contains the polynomial coefficients for the propagation loss as given in Appendix A. The latter stores the occupancy interference statistics as shown in the graphs in Figures 7–10.

The procedure for entering the desired parameters is self–explanatory.

Parameters used in each run can be stored in a file with default filename PARA.DAT or a filename entered by the user. The stored parameters can be restored and displayed in the next run. Changes can be made to the displayed parameters. Once the user has finished entering the new parameters, the program starts the computation. Notes to clarify the characteristics of some parameters are given below. An example is given in the next section.

(a) **Bandwidth and Symbol Rate**

In the case of FSK, the channel bandwidth is defined as the number of tones multiplied by the tone bandwidth. Tone bandwidths are assumed to be contiguous and non–overlapping. In the case of PSK, the channel bandwidth is assumed to be equal to the tone bandwidth (note: there is always one tone in each channel in PSK). The symbol rate is determined by the tone filter bandwidth divided by a factor of 2.

(b) **Number of Jammers in Each Channel**

In the case of FSK with frequency hopping, it is assumed that there is at most one jammer, either a noise or tone jammer, in each channel, i.e. at most one of the M tone–channels is jammed. This applies to both follower and partial–band jamming cases. The condition is optimal for the jammer, i.e. maximum error rate for a fixed total jamming power and number of jammed channels.

(c) **Type of Ground**

Five types of ground can be selected. Multiple inputs are allowed for the transmission between the transmitter and receiver, whereas only one input is allowed for the transmission between the jammer and receiver.

(d) **Type of Interference**

Occupancy noise statistics used in the program are derived from experimental data, they contain both man–made noise, natural noise and interferences from other users, as well as inter–channel mean power level variations. For man–made

noise, natural noise and interference from other users are not included.

(e) **Accuracy of Results**

In general, results falling between 0.1 and 10^{-6} are reasonably accurate. For values below 10^{-6}, inaccuracy may result due to use of single precision in some calculations. For values higher than 0.1, inaccuracy may result in the translation from symbol error rate to bit error rate in the cases of PSK as mentioned in Section 8.

(f) **Display of Results**

Results can be displayed in graphical form with bit error rate versus signal to noise ratio. Here noise refers to either the occupancy interference or man–made noise, not the jamming noise. In the case of occupancy interference, the noise level refers to the *expected* noise level calculated in watts, as defined by occupancy distribution. It should be noted that the resultant error rate is more sensitive to the upper tail of the occupancy distribution curve which has higher noise values and hence lower signal–to–noise ratios. Since the error rate increases exponentially with decreasing signal–to–noise ratio, a much higher error rate occurs at the upper end of the occupancy curve. Therefore the shape of the upper tail of the occupancy curve, rather than the expected value, dominates the overall error rate. The bit error rate axis ranges from 10^{-10} to 1 on a log scale. Values lower than 10^{-10} are displayed on the axis, i.e. at 10^{-10}. The signal to noise ratio axis ranges from –20 to 100 dB. Values beyond these ranges are not displayed. Plots for the parameter with multiple inputs are displayed in different colours and symbols, and a legend is generated.

(g) **Other System Losses**

System losses pertaining to specific details of the system design, such as loss due to imperfection of a synchronization scheme, are not included. However, such losses, if known, can be subtracted from the transmitted signal power when entered by the user.

(h) **Signal–to–Noise Ratio and Signal–to Jammer Ratio**

In the case of FSK, signal–to–noise ratio refers to the ratios of signal power to noise power in the tone–channel which is occupied by the transmitted signal. Noise power in the unoccupied tone–channels are not included. A similar definition applies to E_b/N_0. In contrast, signal–to–jammer ratio refers to the ratio of signal power to jammer power in each tone channel, where the jamming signal does not necessarily fall in the tone–channel occupied by the transmitted signal.

(i) **Frequency Hopping Time**

The transient time between hops is assumed to be small compared with the baud duration.

9.1 Examples

Two examples of running the program are given below. The first example demonstrates how parameters are input by going through the dialogues. The second example demonstrates how parameters can be restored from an existing parameter file and how each parameter can be modified. User–entered parameters are in bold–type italics. Comments are given in italics. An alphabet entry can be either in lower or upper case.

Example 1:

hf
(*Start the program*)

do you want to restore parameters (y or n) ... ***n***
(*The user can restore input parameters from an existing file or enter them one by one by going through the dialogues.*)

select one variable parameter
(1) type of ground for the transmitter

(2) distance between the transmitter and receiver
(3) transmitter signal power
(4) transmitter antenna gain
(5) receiver antenna gain for the signal
(6) type of interference
(7) carrier frequency
(8) channel bandwidth
(9) receiver antenna directivity factor for noise
enter selection ... ***2***
(*Multiple entry is allowed in one of the above items. In this case, we are interested in seeing how the distance between the transmitter and receiver would affect the bit error rate.*)

enter number of runs (1 – 9) ... *4*
(*A maximum of nine inputs for the distance is allowed.*)

select type of ground:
(1) sea water
(2) wet ground
(3) land
(4) medium dry ground
(5) very dry ground
enter selection for transmitter ... *1*
(*Five selections of terrain types is allowed. This along with the distance determines the propagation loss.*)

enter selection for jammer ... *1*
(*A different type of ground can be selected for the jammer, if desired.*)

enter distance between transmitter and receiver in km ...
enter 4 values ... ***80 100 120 150***
(*Four inputs need to be entered, as specified previously.*)

enter transmit signal power (KW) ... *1*

enter transmit antenna gain (dB) ... *0*
(*This is the antenna gain towards the receiver.*)

enter receive antenna gain (dB) for signal ... *0*
(*The antenna gain for the interference may differ.*)

select type of interference:
(1) occupancy interference
(2) man–made noise
enter selection ... *1*
(*Occupancy interference encompasses the statistics for all kinds of unintentional interferences including signals from other users in a frequency hopping environment.*)

select summer day (1), summer night (2)
winter day (3), or winter night (4) ... *1*
(*Four types of occupancy interference can be selected.*)

enter carrier frequency in MHz (1 – 30 MHz) ... *20*

enter channel bandwidth in KHz ... *24*
(*This is the channel bandwidth. In the case of M–ary FSK, the channel bandwidth is M times the bandwidth of each tone filter. In the case of PSK, the channel bandwidth is equal to* that of *the tone filter.*)

enter receive antenna directivity factor for the
sources of noise in dB ... *0*

enter distance between jammer and receiver in km ... *100*

enter total jamming signal power (KW) ... *20*
(*For partial–band jammer, the power is split to cover all jammed channels. For follower jamming, the power is concentrated to one channel at a time.*)

enter jammer antenna gain (dB) ... *0*

enter receiver antenna gain (dB) for jammer ... ***0***

select modulation type: FSK (1) or PSK (2) ... ***1***
(*Either FSK or PSK can be selected.*)

Select modulation scheme and jammer
(1) BFSK without frequency hopping
(2) BFSK with follower jammer
(3) BFSK with partial–band jammer
(4) MFSK with follower jammer
(5) MFSK with partial–band jammer
enter selection ... ***5***

type of jammer, noise (n) or tone (t) jammer ... ***n***

enter number of available channels ... ***20***
enter number of jammed channels ... ***10***
(*The number of jammed channels must be less than or equal to the number of available channels.*)

enter number of bits per symbol (>1) ... ***3***

symbol rate (symbols/sec.): 1500.0
(*The symbol rate is calculated by dividing the tone filter bandwidth by 2.*)

error correcting code used, y or n ... ***y***
(*Block code is used.*)
enter block length (symbols) ... ***10***
enter number of parity symbols per block ... ***5***

signal to noise ratio (dB):
36.1 30.6 25.5 18.2
signal to jammer ratio (dB):
2.5 –3.0 –8.1 –15.3
(*These are the calculated signal to noise ratios and the signal to jammer ratios, in the*

sequence of the distance between the transmitter and receiver that were entered. See note [a] above.)

symbol error rate without coding:

.74E–01 .27E+00 .38E+00 .42E+00

(*These are the predicted symbol error rates without coding in the sequence of the distances between the transmitter and receiver that were entered.*)

symbol error rate with coding:

.16E–01 .26E+00 .41E+00 .47E+00

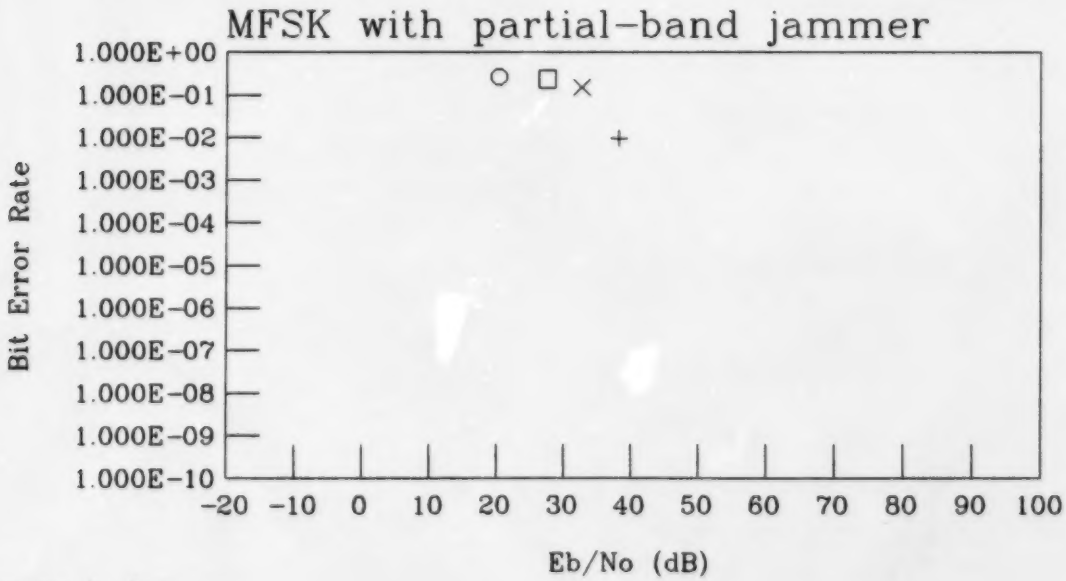
bit error rate with coding:

.94E–02 .15E+00 .24E+00 .27E+00

(*These are the predicted bit error rates with coding in the sequence of the distances between the transmitter and receiver that were entered.*)

display result, y or n ... **n**

(*The user can display the above result with bit error rate versus signal to noise ratio. The displayed is illustrated as follows:*)



do you want a hard copy, y or n ... ***y***
(*A hard copy includes a printout of the above display, a listing of the parameters and the predicted error rates.*)

ENTERING ENDPLT...
(*A hard copy is being printed.*)

do you want to store the updated parameters (y or n) ... ***y***
(*The above parameters can be stored in a file.*)

do you want to store in another file (y or n) ... ***n***
(*The parameters can be stored in the default file PARA.DAT if entered 'n', or in a file with filename specified by the user if entered 'y'.*)

do you want another run (y or n) ... ***n***
(*Another run can be made without leaving the program.*)

Example 2:

hf
(*Start the program*)

do you want to restore parameters (y or n) ? ... ***y***
(*Parameters from the previous run can be restored. This would save the user from entering all the necessary parameters.*)

enter parameter file name
enter "d" if you want the default file ... ***d***
(*The user can restore parameters from the default file PARA.DAT, if it exists. Alternatively, the user can specify an existing file which contains the desired parameters.*)

(1) type of ground for tx: sea water ,
(2) distance between tx and rx (km): 80. 100. 120. 150.
(3) transmit signal power (KW): 1.00
(4) transmit antenna gain (dB): 0.0

(5) receive antenna gain for signal (dB): 0.0
(6) occupancy interference: summer day,
(7) carrier frequency (MHz): 20.0
(8) channel bandwidth (KHz): 24.0
(9) receive antenna gain for noise (dB): 0.0
(10) type of ground for jammer: sea water
(11) distance between jammer and receiver (km): 100.
(12) total jamming power (KW): 20.0
(13) jammer antenna gain (dB): 0.0
(14) receive antenna gain for jammer (dB): 0.0
(15) MFSK with partial–band jammer
(16) type of jammer: noise
(17) number of available channels: 20.
(18) number of jammed channels: 10.
(19) number of bits per symbol: 3
(20) block coding is used
(21) block code block length: 10
(22) number of parity symbols: 5
(*The values of the parameters are displayed. Multiple entry is allowed in one of items 1 – 9. In this case, the parameters are restored from Example 1.*)

do you want to change parameters (y or n) ? ... ***y***
(*The user can modify the parameters if he wishes.*)

enter item number to be changed ... ***2***
enter number of inputs (1 – 9) ... ***1***
(*Only one parameter is allowed to have multiple entry. To select another parameter for multiple entry, one must change the current parameter with multiple entry to a single entry parameter. Multiple entry is allowed for items 1 – 9 with a maximum number of inputs of 9. Single entry is allowed for items 10 – 22.*)

enter values ... ***100***

(1) type of ground for tx: sea water ,
(2) distance between tx and rx (km): 100. (*value is now changed to 100*)

(3) transmit signal power (KW): 1.00
(4) transmit antenna gain (dB): 0.0
(5) receive antenna gain for signal (dB): 0.0
(6) occupancy interference: summer day,
(7) carrier frequency (MHz): 20.0
(8) channel bandwidth (KHz): 24.0
(9) receive antenna gain for noise (dB): 0.0
(10) type of ground for jammer: sea water
(11) distance between jammer and receiver (km): 100.
(12) total jamming power (KW): 20.0
(13) jammer antenna gain (dB): 0.0
(14) receive antenna gain for jammer (dB): 0.0
(15) MFSK with partial–band jammer
(16) type of jammer: noise
(17) number of available channels: 20.
(18) number of jammed channels: 10.
(20) number of bits per symbol: 3
(21) block coding is used
(22) block code block length: 10
(23) number of parity symbols: 5
(A listing of all parameters is displayed after each update.)

do you want to change parameters (y or n) ? ... ***y***
(*The user can continue to make if he wishes.*)

enter item number to be changed ... ***3***
(*Item 3 is selected to change the transmitter power.*)

enter number of inputs (1 – 9) ... ***5***
(*Multiple entry is allowed since no other parameter has multiple entry.*)

enter values ... ***1 2 3 4 5***

(1) type of ground for tx: sea water ,
(2) distance between tx and rx (km): 100.

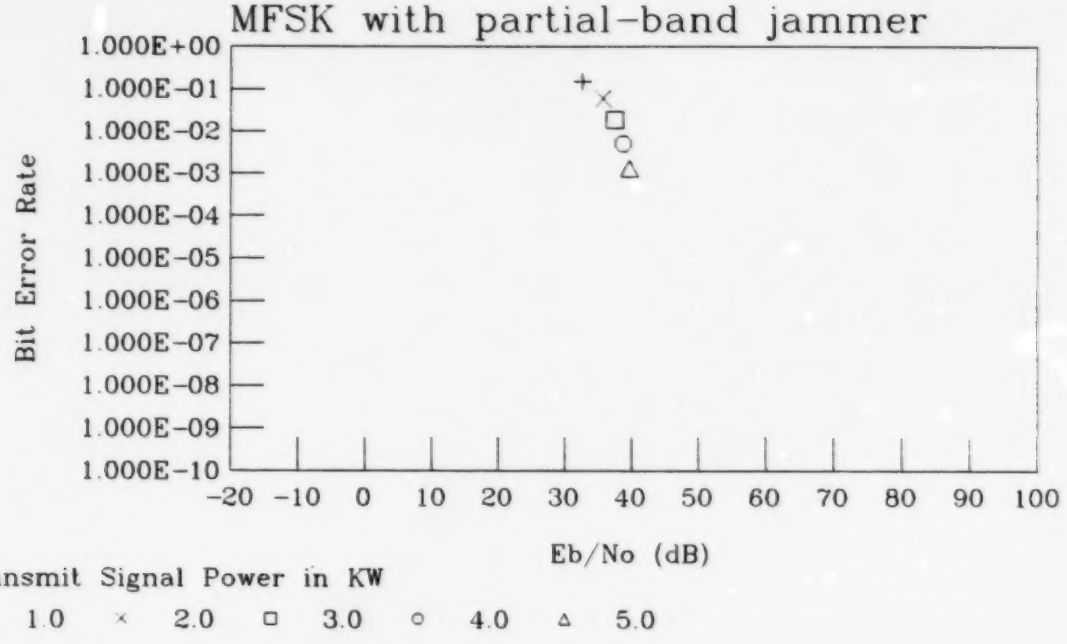
(3) transmit signal power (KW): 1.00 2.00 3.00 4.00 5.00 (*new multiple entries*)
(4) transmit antenna gain (dB): 0.0
(5) receive antenna gain for signal (dB): 0.0
(6) occupancy interference: summer day,
(7) carrier frequency (MHz): 20.0
(8) channel bandwidth (KHz): 24.0
(9) receive antenna gain for noise (dB): 0.0
(10) type of ground for jammer: sea water
(11) distance between jammer and receiver (km): 100.
(12) total jamming power (KW): 20.0
(13) jammer antenna gain (dB): 0.0
(14) receive antenna gain for jammer (dB): 0.0
(15) MFSK with partial–band jammer
(16) type of jammer: noise
(17) number of available channels: 20.
(18) number of jammed channels: 10.
(20) number of bits per symbol: 3
(21) block coding is used
(22) block code block length: 10
(23) number of parity symbols: 5

do you want to change parameters (y or n) ? ... **n**
(*Once the user is satisfied with all the changes, he can enter "n" to proceed the calculation of error rates.*)

signal to noise ratio (dB):
32.6 35.6 37.4 38.7 39.6
signal to jammer ratio (dB):
–3.0 0.0 1.8 3.0 4.0
symbol error rate without coding:
.27E+00 .16E+00 .98E–01 .59E–01 .36E–01
symbol error rate with coding:
.26E+00 .10E+00 .33E–01 .91E–02 .23E–02
bit error rate with coding:
.15E+00 .60E–01 .19E–01 .52E–02 .13E–02

display result, y or n ... *y*

(*The user can display the above result with bit error rate versus signal to noise ratio. The displayed is illustrated as follow.*)



do you want a hard copy, y or n ... *y*

(*A hard copy of the above graph and a listing of all the parameters and results can be printed.*)

ENTERING ENDPLT...

(*A hard copy is being printed.*)

do you want to store the updated parameters (y or n) ? ... *y*

do you want to store in another file (y or n) ? ... *n*

(*The parameters can be stored in the default file PARA.DAT if "n" is entered, or a file specified by the user if "y" is entered.*)

do you want another run (y or n) ? ... *n*

(*The user can make another run without leaving the program.*)

10 Acknowledgements

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Appendix A

Propagation Coefficients

The field strength curves given in CCIR report [1] are curve–fitted with fifth–order polynomial equations, viz.

$$E_r = p_0 + p_1 x + p_2 x^2 + p_3 x^3 + p_4 x^4 + p_5 x^5$$

where E_r is field strength in dBW (see Eq.2) and $x = \log_{10} d$, d is distance in km.

	Coefficients					
Frequency MHz	p_0	p_1	p_2	p_3	p_4	p_5
Sea Water						
1	110.1	–28.18	22.03	–23.32	10.81	–1.84
1.5	110.1	–28.63	24.43	–26.6	12.44	–2.121
2.	110.	–26.23	17.55	–20.12	10.01	–1.821
3.	110.	–27.19	20.75	–23.56	11.54	–2.086
4.	110.1	–30.39	30.49	–33.21	15.42	–2.657
5.	110.	–28.	23.5	–26.64	13.05	–2.391
7.5	110.1	–30.65	31.86	–35.11	16.6	–2.987
10.	110.	–21.58	4.764	–9.229	6.599	–1.708
15.	110.	–29.3	31.03	–37.51	18.66	–3.656
20.	110.	–31.85	41.3	–51.28	24.93	–4.707
30.	110.	–36.2	53.68	–71.06	35.48	–6.672
Wet Ground						
1.	110.	–26.07	18.58	–21.96	9.224	–1.588
1.5	110.	–31.57	34.79	–45.65	20.74	–3.414
2.	109.2	–29.26	25.9	–41.59	20.78	–3.633

3.	107.6	–35.22	28.1	–45.16	23.77	–4.333
4.	105.	–32.43	10.14	–27.27	17.14	–3.515
5.	103.1	–35.01	6.37	–18.75	12.49	–2.752
7.5	98.1	–35.04	4.209	–16.27	11.75	–2.766
10.	95.98	–40.67	8.372	–16.57	11.48	–2.788
15.	92.04	–41.33	5.094	–9.859	7.659	–2.148
20.	88.01	–36.57	2.781	–16.39	14.16	–3.766
30.	85.01	–43.77	18.26	–26.14	14.98	–3.318

Land

1.	108.1	–22.51	16.77	–35.67	18.6	–3.249
1.5	106.9	–34.41	33.45	–53.14	27.26	–4.756
2.	105.	–31.98	10.54	–26.11	15.54	–3.046
3.	102.	–36.93	1.635	–9.702	7.588	–1.864
4.	97.99	–34.85	–4.614	–5.19	6.783	–1.94
5.	95.98	–40.3	7.742	–17.78	12.7	–2.976
7.5	91.21	–45.58	29.4	–42.95	24.47	–4.94
10.	88.08	–36.26	–8.057	3.447	1.79	–1.182
15.	84.05	–39.78	4.05	–11.33	9.626	–2.726
20.	82.02	–42.49	11.47	–17.76	11.86	–3.055
30.	77.98	–42.77	22.31	–41.33	28.42	–6.835

Medium Dry Ground

1.	105.	–26.51	4.961	–21.95	13.78	–2.704
1.5	102.1	–29.54	–1.249	–11.85	9.261	–2.091
2.	100.	–34.26	3.433	–14.19	9.95	–2.211
3.	96.99	–36.86	2.894	–10.85	8.161	–1.968
4.	94.96	–43.48	23.2	–34.22	19.27	–3.853
5.	93.04	–37.77	4.379	–13.03	9.711	–2.373
7.5	90.02	–43.25	15.2	–22.83	13.8	–3.049
10.	87.57	–43.11	16.35	–25.96	16.24	–3.661
15.	84.18	–47.52	23.08	–28.33	15.98	–3.561
20.	81.08	–38.19	2.728	–11.49	9.74	–2.724

30.	78.	–41.61	8.793	–15.18	10.83	–2.994

Very Dry Ground

1.	97.12	–41.5	15.75	–22.55	12.44	–2.431
1.5	93.02	–35.23	3.413	–14.12	9.992	–2.191
2.	91.04	–37.1	0.8511	–6.896	5.8	–1.489
3.	88.08	–38.03	–0.3176	–4.804	5.109	–1.491
4.	86.01	–41.59	7.804	–12.52	8.32	–2.006
5.	82.99	–36.04	–1.31	–4.174	4.311	–1.29
7.5	79.98	–42.93	19.63	–29.77	17.55	–3.728
10.	77.54	–41.04	11.75	–20.4	13.17	–3.04
15.	74.08	–45.37	27.32	–38.68	22.35	–4.787
20.	72.05	–46.3	27.86	–40.23	24.15	–5.331
30.	67.99	–34.27	–7.37	–1.864	6.081	–2.292

Appendix B

Derivations of M-ary FSK

We assume that *at most one jammer* is used to jam the M channels. This is an optimized condition for the jammer in a frequency hopping scheme. The jammer may fall into the transmission channel or one of the M–1 complementary channels. In a frequency hopping system, three cases are possible, namely,

Case 1: The jammer falls into the transmission channel and adds with the transmit signal.

Case 2: The jammer falls into one of the M–1 complementary channels.

Case 3: The jammer does not exist.

In all cases, unintentional noise interference exists.

The probabilities of symbol error in the cases are given as follows:

Case 1:

$$P_{s1} = 1 - \int_0^{\infty} f_1(r_1) \left(\int_0^{r_1} f_4(r_4)\, dr_4 \right)^{M-1} dr_1 \qquad \text{(B–1)}$$

Case 2:

$$P_{s2} = 1 - \int_0^{\infty} f_3(r_3) \left(\int_0^{r_3} f_2(r_2)\, dr_2 \right) \left(\int_0^{r_3} f_4(r_4)\, dr_4 \right)^{M-2} dr_3 \qquad \text{(B–2)}$$

Case 3:

$$P_{s3} = 1 - \int_0^{\infty} f_3(r_3) \left(\int_0^{r_3} f_4(r_4)\, dr_4 \right)^{M-1} dr_3 \qquad \text{(B–3)}$$

where

f_1 is the probability density function with transmit signal, jammer and noise,
f_2 is the probability density function with jammer and noise,
f_3 is the probability density function with transmit signal and noise,
f_4 is the probability density function with noise only.

The averaged probability of error for a jammed channel is given by

$$P_{s_J} = \frac{1}{M} P_{s1} + \frac{M-1}{M} P_{s2} \qquad \text{(B–4)}$$

P_{s3} is used to calculate the overall probability of error in a frequency hopping system where some of the channels are not jammed.

B.1 *M*–ary FSK with Tone Jammer

For FSK with a tone jammer, the probability density functions are given as follows:

$$f_1(r_1) = \frac{r_1}{N} \exp\left[-\frac{D^2 + r_1^2}{2N}\right] \mathrm{I}_0\left[\frac{D r_1}{N}\right] \qquad \text{(B–5)}$$

$$f_2(r_2) = \frac{r_2}{N} \exp\left[-\frac{B^2 + r_2^2}{2N}\right] \mathrm{I}_0\left[\frac{B r_2}{N}\right] \qquad \text{(B–6)}$$

$$f_3(r_3) = \frac{r_3}{N} \exp\left[-\frac{A^2 + r_3^2}{2N}\right] \mathrm{I}_0\left[\frac{A r_3}{N}\right] \qquad \text{(B–7)}$$

$$f_4(r_4) = \frac{r_4}{N} \exp\left[-\frac{r_4^2}{2N}\right] \qquad \text{Note: } \int_0^{\eta} f_4(r_4)\, dr_4 = 1 - e^{-\frac{\eta^2}{2N}} \qquad \text{(B–8)}$$

where

N is the unintentional noise power,

A is the signal amplitude, $= \sqrt{2S}$, S is the signal power,

B is the tone jammer amplitude, $= \sqrt{2J}$, J is the tone jammer power,

$D^2 = A^2 + B^2 + 2AB \cos x$, x is the phase angle between the signal and tone jammer.

Case 1:

$$P_{s1}(x) = 1 - \int_0^\infty f_1(r_1) \left(\int_0^{r_1} f_4(r_4)\, dr_4 \right)^{M-1} dr_1$$

$$= 1 - \int_0^\infty \frac{r_1}{N} \exp\left[-\frac{D^2 + r_1^2}{2N} \right] I_0\left[\frac{D r_1}{N} \right] \left[1 - e^{-\frac{r_1^2}{2N}} \right]^{M-1} dr_1$$

$$= 1 - \int_0^\infty \frac{r_1}{N} \exp\left[-\frac{D^2 + r_1^2}{2N} \right] I_0\left[\frac{D r_1}{N} \right] \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} e^{-\frac{j r_1^2}{2N}} dr_1$$

$$= 1 - \int_0^\infty \frac{r_1}{N} \exp\left[-\frac{D^2 + r_1^2}{2N} \right] I_0\left[\frac{D r_1}{N} \right] \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} e^{-\frac{j r_1^2}{2N}} dr_1$$

$$= 1 - e^{-\frac{D^2}{2N}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \int_0^\infty \frac{r_1}{N} e^{-\frac{r_1^2}{2N}(j+1)} I_0\left[\frac{D r_1}{N} \right] dr_1 \qquad \text{(B–9)}$$

where $P_{s1}(x)$ is designated as a function of x, phase angle inherited from D.

To evaluate the last integral in (B–9), we have

$$\int_0^\infty \frac{r_1}{N} e^{-\frac{r_1^2}{2N}(j+1)} I_0\left[\frac{D r_1}{N}\right] dr_1$$

$$= e^{\frac{D^2}{2N(j+1)}} \int_0^\infty \frac{r_1}{N} e^{-\left[\frac{r_1^2}{2N}(j+1)+\frac{D^2}{2N(j+1)}\right]} I_0\left[\frac{D r_1}{N}\right] dr_1 \qquad \text{(B–10)}$$

Let $R^2 = \frac{r_1^2}{N}(j+1), \quad R\,dR = \frac{j+1}{N} r_1 dr_1$ (B–11)

$$G^2 = \frac{D^2}{N(j+1)} \qquad \text{(B–12)}$$

Substituting (B–11) and (B–12) into (B–10), we have

$$\int_0^\infty \frac{r_1}{N} e^{-\frac{r_1^2}{2N}(j+1)} I_0\left[\frac{D r_1}{N}\right] dr_1 = \frac{1}{j+1} e^{\frac{D^2}{2N(j+1)}} \int_0^\infty R\, e^{-\frac{R^2+G^2}{2}} I_0(GR)\, dR$$

$$= \frac{1}{j+1} e^{\frac{D^2}{2N(j+1)}}$$

since $\int_0^\infty R\, e^{-\frac{R^2+G^2}{2}} I_0(GR)\, dR = 1$ (B–13)

Substituting (B–13) into (B–9), we have

$$P_{s1} = 1 - e^{-\frac{D^2}{2N}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \frac{1}{j+1} e^{\frac{D^2}{2N(j+1)}}$$

$$= 1 - \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \frac{1}{j+1} e^{-\frac{D^2}{2N}\left[\frac{j}{j+1}\right]} \qquad \text{(B–14)}$$

Let $i = j+1$, (B–14) becomes

$$P_{s1}(x) = 1 - \frac{1}{M}\sum_{i=1}^{M}(-1)^i \begin{bmatrix} M \\ i \end{bmatrix} e^{-\frac{D^2}{2N}\left[1-\frac{1}{i}\right]}$$

$$= \frac{1}{M}\sum_{i=2}^{M}(-1)^i \begin{bmatrix} M \\ i \end{bmatrix} e^{-\frac{D^2}{2N}\left[1-\frac{1}{i}\right]} \qquad \text{(B–15)}$$

But D is a function of the phase angle x. Averaging P_{s1} in (B–15) over 2π, we have

$$P_{s1} = \int_0^{2\pi} P_{s1}(x)\,dx$$

$$= \int_0^{2\pi} \frac{1}{M}\sum_{i=2}^{M}(-1)^i \begin{bmatrix} M \\ i \end{bmatrix} e^{-\frac{D^2}{2N}\left[1-\frac{1}{i}\right]}\,dx$$

$$= \frac{1}{M}\sum_{i=2}^{M}(-1)^i \begin{bmatrix} M \\ i \end{bmatrix} e^{-\frac{1}{2N}\left[1-\frac{1}{i}\right](A^2+B^2)} \int_0^{2\pi} \exp\left[\left[\frac{AB\left[1-\frac{1}{i}\right]}{N}\right]\cos x\right] dx$$

for $D^2 = A^2 + B^2 + 2AB\cos x$

$$= \frac{1}{M}\sum_{i=2}^{M}(-1)^i \begin{bmatrix} M \\ i \end{bmatrix} e^{-\frac{1}{2N}\left[1-\frac{1}{i}\right](A^2+B^2)} I_0\left[\frac{AB\left[1-\frac{1}{i}\right]}{N}\right] \qquad \text{(B–16)}$$

For $\dfrac{AB\left[1-\frac{1}{i}\right]}{N} > 10$, in order to prevent $I_0(.)$ in (B–16) from overflowing we use the identity $I_0(z) \cong \dfrac{e^z}{\sqrt{2\pi z}}$,

$$P_{s1} \cong \frac{1}{M} \sum_{i=2}^{M} (-1)^i \binom{M}{i} e^{-\frac{1}{2N}\left[1-\frac{1}{i}\right](A^2+B^2)} \exp\left[\frac{AB\left[1-\frac{1}{i}\right]}{N}\right] \left[\frac{2\pi AB\left[1-\frac{1}{i}\right]}{N}\right]^{-\frac{1}{2}}$$

$$\cong \frac{1}{M}\sqrt{\frac{N}{2\pi AB}} \sum_{i=2}^{M} (-1)^i \binom{M}{i} e^{-\frac{1}{2N}\left[1-\frac{1}{i}\right](A-B)^2} \left[1-\frac{1}{i}\right]^{-\frac{1}{2}} \qquad \text{(B–17)}$$

Case 2:

$$P_{s2} = 1 - \int_0^\infty f_3(r_3) \left(\int_0^{r_3} f_2(r_2)\, dr_2 \right) \left(\int_0^{r_3} f_4(r_4)\, dr_4 \right)^{M-2} dr_1$$

$$= 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \int_0^{r_3} \frac{r_2}{N} \exp\left[-\frac{B^2+r_2^2}{2N}\right] I_0\left[\frac{B r_2}{N}\right] dr_2$$

$$\left[1 - e^{-\frac{r_3^2}{2N}}\right]^{M-2} dr_3 \qquad \text{(B–18)}$$

The middle integral can be related to the Marcum Q–function, i.e.

$$\int_0^{r_3} \frac{r_2}{N} \exp\left[-\frac{B^2+r_2^2}{2N}\right] I_0\left[\frac{B r_2}{N}\right] dr_2 = 1 - \int_{r_3}^\infty \frac{r_2}{N} \exp\left[-\frac{B^2+r_2^2}{2N}\right] I_0\left[\frac{B r_2}{N}\right] dr_2$$

$$= 1 - Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] \qquad \text{(B–19)}$$

Substituting (B–19) into (B–18), we have

$$P_{s2} = 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \left[1 - Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right]\right] \left[1 - e^{-\frac{r_3^2}{2N}}\right]^{M-2} dr_3$$

$$= 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \left[1 - Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right]\right] \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{j r_3^2}{2N}} dr_3$$

$$= 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{j r_3^2}{2N}} dr_3$$

$$+ \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{j r_3^2}{2N}} Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] dr_3$$

$$= \frac{1}{M-1} \sum_{i=0}^{M-1} (-1)^i \binom{M-1}{i} e^{-\frac{A^2}{2N}\left[1-\frac{1}{i}\right]}$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{A^2}{2N}} \int_0^\infty \frac{r_3}{N} e^{-\frac{r_3^2(1+j)}{2N}} I_0\left[\frac{A r_3}{N}\right] Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] dr_3 \qquad \text{(B–20)}$$

Using the identity (p.14, [5]),

$$\int_0^\infty x\, e^{-\frac{x^2+a^2}{2}} I_0(ax)\, Q(b, rx) = Q(v_2, v_1) - \frac{r^2}{1+r^2} \exp\left[-\frac{a^2r^2+b^2}{2(1+r^2)}\right] I_0\left[\frac{a\,b\,r}{1+r^2}\right] \qquad \text{(B–21)}$$

$$v_1 = \frac{a\,r}{\sqrt{1+r^2}}, \quad v_2 = \frac{b}{\sqrt{1+r^2}}$$

we compute the last integral in (B–20) as

$$\int_0^\infty \frac{r_3}{N} e^{-\frac{r_3^2(1+j)}{2N}} I_0\left[\frac{A r_3}{N}\right] Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] dr_3$$

$$= e^{\frac{A^2}{2N(j+1)}} \int_0^\infty \frac{r_3}{N} e^{-\left[\frac{r_3^2(1+j)}{2N} + \frac{A^2}{2N(j+1)}\right]} I_0\left[\frac{A r_3}{N}\right] Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] dr_3 \quad \text{(B–22)}$$

Let $R^2 = \frac{r_3^2}{N}(j+1), \quad R\,dR = \frac{j+1}{N} r_3 dr_3$ (B–23)

$$H^2 = \frac{A^2}{N(j+1)} \quad \text{(B–24)}$$

Substituting (B–23) and (B–24) into (B–22), we have

$$e^{\frac{A^2}{2N(j+1)}} \int_0^\infty R\, e^{-\left[\frac{R^2+H^2}{2N}\right]} I_0(HR)\, Q\left[\frac{B}{\sqrt{N}}, \frac{1}{\sqrt{j+1}} R\right] dR \quad \text{(B–25)}$$

Use the identity (B–21), and let

$$b = \frac{B}{\sqrt{N}}$$

$$r = \frac{1}{\sqrt{j+1}}$$

$$a^2 = H^2 = \frac{A^2}{N(j+1)}$$

(B–22) can be written as

$$\int_0^\infty \frac{r_3}{N} e^{-\frac{r_3^2(1+j)}{2N}} I_0\left[\frac{A r_3}{N}\right] Q\left[\frac{B}{\sqrt{N}}, \frac{r_3}{\sqrt{N}}\right] dr_3$$

$$= e^{\frac{A^2}{2N(j+1)}} \left\{ Q(v_2, v_1) - \frac{1}{j+2} \exp\left[- \frac{\frac{A^2}{N(j+2)} + \frac{B^2}{N}(j+1)}{2(j+1)} \right] \quad \left[\frac{AB}{N(j+2)} \right] \right\} \qquad \text{(B–26)}$$

where

$$v_1 = \frac{A}{\sqrt{N(j+1)(j+2)}}, \text{ and } \quad v_2 = B \sqrt{\frac{j+1}{N(j+2)}}$$

Substituting (B–26) into (B–20), we have

$$P_{s2} = \frac{1}{M-1} \sum_{i=2}^{M-1} (-1)^i \binom{M-1}{i} \exp\left[- \frac{A^2}{2N} \left[1 - \frac{1}{i} \right] \right]$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} \exp\left[- \frac{A^2 j}{2N(j+1)} \right] \times$$

$$\left\{ Q(v_2, v_1) - \frac{1}{j+2} \exp\left[- \frac{\frac{A^2}{N(j+2)} + \frac{B^2}{N}(j+1)}{2(j+1)} \right] I_0\left[\frac{AB}{N(j+2)} \right] \right\} \qquad \text{(B–27)}$$

where Q(.,.) is the Marcum Q–function, and

$$v_1 = \frac{A}{\sqrt{N(j+1)(j+2)}}, \text{ and } \quad v_2 = \sqrt{\frac{j+1}{N(j+2)}}$$

Case 3:

$$P_{s3} = 1 - \int_0^{\infty} f_3(r_3) \left(\int_0^{r_3} f_4(r_4)\, dr_4 \right)^{M-1} dr_3$$

$$= 1 - \int_0^{\infty} \frac{r_3}{N} \exp\left[- \frac{A^2 + r_3^2}{2N} \right] I_0\left[\frac{A r_3}{N} \right] \left[1 - e^{-\frac{r_3^2}{2N}} \right]^{M-1} dr_3$$

$$P_{s3} = \frac{1}{M} \sum_{i=2}^{M} (-1)^i \binom{M}{i} \exp\left[-\frac{A^2}{2N}\left[1 - \frac{1}{i}\right]\right] \tag{B–28}$$

Symbol Error Rate with Partial Band Jamming

In partial band jamming, N_J channels out of a total of N_C channels are jammed, where $N_J \leq N_C$ The overall symbol error rate is given by

$$P_s = \left[\frac{1}{M} P_{s1} + \frac{M-1}{M} P_{s2}\right] \frac{N_J}{N_C} + \frac{N_C - N_J}{N_C} P_{s3} \tag{B–29}$$

B.2 *M*–ary FSK with Noise Jammer

For FSK with a noise jammer, the probability density functions are given as follows:

$$f_1(r_1) = \frac{r_1}{N+J} \exp\left[-\frac{A^2 + r_1^2}{2(N+J)}\right] I_0\left[\frac{A r_1}{N+J}\right] \tag{B–30}$$

$$f_2(r_2) = \frac{r_2}{N+J} \exp\left[-\frac{r_2^2}{2(N+J)}\right] \tag{B–31}$$

$$f_3(r_3) = \frac{r_3}{N} \exp\left[-\frac{A^2 + r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \tag{B–32}$$

$$f_4(r_4) = \frac{r_4}{N} \exp\left[-\frac{r_4^2}{2N}\right] \tag{B–33}$$

where

N is the unintentional noise power,
A is the signal amplitude, $= \sqrt{2S}$, S is the signal power,
J is the noise jammer power.

Case 1:

$$P_{s1} = 1 - \int_0^\infty f_1(r_1) \left(\int_0^{r_1} f_4(r_4)\, dr_4 \right)^{M-1} dr_1$$

$$= 1 - \int_0^\infty \frac{r_1}{N+J} \exp\left[-\frac{A^2 + r_1^2}{2(N+J)} \right] I_0\left[\frac{A r_1}{N+J} \right] \left[1 - e^{-\frac{r_1^2}{2N}} \right]^{M-1} dr_1$$

$$= 1 - \int_0^\infty \frac{r_1}{N+J} \exp\left[-\frac{A^2 + r_1^2}{2(N+J)} \right] I_0\left[\frac{A r_1}{N+J} \right] \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} e^{-\frac{j r_1^2}{2N}} dr_1$$

$$= 1 - e^{-\frac{A}{2N'}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \int_0^\infty \frac{r_1}{N'} e^{-\left[\frac{r_1^2}{2N'} + \frac{j r_1^2}{2N} \right]} I_0\left[\frac{A r_1}{N'} \right] dr_1$$

$$= 1 - e^{-\frac{A}{2N'}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \exp\left[\frac{A^2}{2N'^2 \left[\frac{1}{N'} + \frac{j}{N} \right]} \right] \times$$

$$\int_0^\infty \frac{r_1}{N'} \exp\left[-\left(\frac{r_1^2}{2} \left[\frac{1}{N'} + \frac{j}{N} \right] + \left[\frac{A^2}{2N'^2 \left[\frac{1}{N'} + \frac{j}{N} \right]} \right] \right) \right] I_0\left[\frac{A r_1}{N'} \right] dr_1$$

where $N' = N + J$ (B–34)

Let $R^2 = r_1^2 \left[\frac{1}{N'} + \frac{j}{N} \right]$, $R\, dR = r_1 \left[\frac{1}{N'} + \frac{j}{N} \right] dr_1$

$$L^2 = \frac{A^2}{N'^2 \left[\frac{1}{N'} + \frac{j}{N} \right]}$$

(B–34) becomes

$$= 1 - e^{-\frac{A}{2N'}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \exp\left[\frac{A^2}{2N'^2 \left[\frac{1}{N'} + \frac{j}{N} \right]} \right] \frac{1}{N' \left[\frac{1}{N'} + \frac{j}{N} \right]} \times$$

$$\int_0^\infty R\, e^{-\frac{R^2+L^2}{2}} I_0(LR)\, dR$$

$$= 1 - e^{-\frac{A}{2N'}} \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \exp\left[\frac{A^2}{2N'^2\left[\frac{1}{N'}+\frac{j}{N}\right]}\right] \frac{1}{N'\left[\frac{1}{N'}+\frac{j}{N}\right]}$$

since $\int_0^\infty R\, e^{-\frac{R^2+L^2}{2}} I_0(LR)\, dR = 1$

$$= 1 - \sum_{j=0}^{M-1} (-1)^j \binom{M-1}{j} \exp\left[-\frac{A^2}{2}\left[\frac{1}{N'}+\frac{j}{N}\right]\right] \frac{1}{\left[1+j\frac{N'}{N}\right]} \qquad \text{(B–35)}$$

Case 2:

$$P_{s2} = 1 - \int_0^\infty f_3(r_3) \left(\int_0^{r_3} f_2(r_2)\, dr_2 \right) \left(\int_0^{r_3} f_4(r_4)\, dr_4 \right)^{M-2} dr_3$$

$$= 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \left[1 - e^{-\frac{r_3^2}{2N'}}\right] \left[1 - e^{-\frac{r_3^2}{2N}}\right]^{M-2} dr_3$$

$$= 1 - \int_0^\infty \frac{r_3}{N} \exp\left[-\frac{A^2+r_3^2}{2N}\right] I_0\left[\frac{A r_3}{N}\right] \left[1 - e^{-\frac{r_3^2}{2N'}}\right] \times$$

$$\sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{j r_3^2}{2N}}\, dr_3$$

$$= 1 - \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{A^2}{2N}} \int_0^\infty \frac{r_3}{N} e^{-\frac{r_3^2}{2N}(j+1)} I_0\left[\frac{A r_3}{N}\right] dr_3$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} e^{-\frac{A^2}{2N}} \int_0^\infty \frac{r_3}{N} e^{-\frac{r_3^2}{2}\left[\frac{1}{N}+\frac{j+1}{N}\right]} I_0\left[\frac{A r_3}{N}\right] dr_3$$

$$= \frac{1}{M-1} \sum_{i=2}^{M-1} (-1)^i \binom{M-1}{i} \exp\left[-\frac{A^2}{2N}\left[1-\frac{1}{i}\right]\right]$$

$$+ \sum_{j=0}^{M-2} (-1)^j \binom{M-2}{j} \frac{1}{\frac{N}{N+J}+j+1} \exp\left[-\frac{A^2}{2N}\left[\frac{N+j(N+J)}{N+(j+1)(N+J)}\right]\right] \quad \text{(B-36)}$$

Case 3:

Same as Case 3 in Section B.1

Appendix C

Derivation of 8–ary PSK with a Tone Jammer

The in–phase and quadrature components of the received signal without noise are given by (p.270, [6])

$$z_I = \sqrt{S} - \sqrt{J}\sin\theta_j \qquad (C\text{–}1)$$
$$z_Q = \sqrt{J}\cos\theta_j$$

where S is the signal power, J is the jamming power in a channel, and θ_j is an arbitrary phase angle of the jammer relative to the signal.

The probability function is given by

$$p(x,y,\theta_j) = \frac{1}{\pi N_t}\exp\left[-\frac{(x-z_I)^2+(y-z_Q)^2}{N_t}\right] \qquad (C\text{–}2)$$

where x, y are the random variables representing the in–phase and quadratic components. Expressing (C–2) in polar coordinate, with $x = r\cos\theta$ and $y = r\sin\theta$, we have

$$p(r,\theta,\theta_j) = \frac{r}{\pi N_t}\exp\left[-\frac{r^2-2r(z_I\cos\theta+z_Q\sin\theta)+(z_I^2+z_Q^2)}{N_t}\right] \qquad (C\text{–}3)$$

The probability of a *correct* detection is

$$P_c = \frac{1}{2\pi}\int_0^{2\pi}\int_{-\frac{\pi}{8}}^{\frac{\pi}{8}}\int_0^{\infty} p(r,\theta,\theta_j)\,dr\,d\theta\,d\theta_j \qquad (C\text{–}4)$$

To evaluate the inner integral, we let

$$A = 2\,(z_I\cos\theta+z_Q\sin\theta) = 2\,[\sqrt{S}\cos\theta + \sqrt{J}\sin(\theta-\theta_j)] \qquad (C\text{–}5)$$

$$B = z_I^2 + z_Q^2 = S + J - 2\sqrt{SJ}\sin\theta_j \tag{C-6}$$

then

$$\frac{1}{\pi N_t}\int_0^{\infty} r\exp\left[-\frac{r^2 - Ar + B}{N_t}\right] dr$$

$$= \frac{1}{2\pi}\exp\left[-\frac{B}{N_t}\right]\left\{1 + \frac{A}{2}\sqrt{\frac{\pi}{N_t}}\exp\left[\frac{A^2}{4N_t}\right]\operatorname{erfc}\left[-\frac{A}{2\sqrt{N_t}}\right]\right\} \tag{C-7}$$

For $\frac{A}{2\sqrt{N_t}} < 2$, the outer two integrals must be evaluated numerically,

$$P_c = \frac{1}{(2\pi)^2}\int_0^{2\pi}\int_{-\frac{\pi}{8}}^{\frac{\pi}{8}}\exp\left[-\frac{B}{N_t}\right]\left\{1 + \frac{A}{2}\sqrt{\frac{\pi}{N_t}}\exp\left[\frac{A^2}{4N_t}\right]\operatorname{erfc}\left[-\frac{A}{2\sqrt{N_t}}\right]\right\} d\theta\, d\theta_j \tag{C-8}$$

For $\frac{A}{2\sqrt{N_t}} > 2$, and using the identity $\operatorname{erfc}(-a) = 2 - \operatorname{erfc}(a)$ and approximation (p.570, [7])

$$\operatorname{erfc}(u) \cong \frac{\exp(-u^2)}{\sqrt{\pi}u} \tag{C-9}$$

then (31) can be simplified as

$$\frac{1}{\pi N_t}\int_0^{\infty} r\exp\left[-\frac{r^2 - Ar + B}{N_t}\right] dr \cong \frac{A}{2N_t\sqrt{\pi}}\exp\left[\frac{A^2}{4N_t} - \frac{B}{N_t}\right] \tag{C-10}$$

To perform the second integral, we have

$$\int_{-\frac{\pi}{8}}^{\frac{\pi}{8}}\int_{0}^{\infty} p(r,\theta,\theta_j)\, dr\, d\theta \cong \int_{-\frac{\pi}{8}}^{\frac{\pi}{8}} \frac{A}{2N_t\sqrt{\pi}} \exp\left[\frac{A^2}{4N_t} - \frac{B}{N_t}\right] dr$$

$$= \frac{1}{2N_t\sqrt{\pi}} \int_{-\frac{\pi}{8}}^{\frac{\pi}{8}} 2\,(z_I\cos\theta + z_Q\sin\theta) \exp\left[\frac{2(z_I\cos\theta+z_Q\sin\theta)^2}{4N_t} - \frac{z_I^2+z_Q^2}{N_t}\right] dr$$

$$= \frac{1}{N_t\sqrt{\pi}} \int_{-\frac{\pi}{8}}^{\frac{\pi}{8}} (z_I\cos\theta + z_Q\sin\theta) \exp\left[-\frac{(z_I\sin\theta - z_Q\cos\theta)^2}{N_t}\right] dr$$

$$= \frac{1}{2}\left[\operatorname{erf}\left[\frac{z_I\sin\theta - z_Q\cos\theta}{\sqrt{N_t}}\right]\right]_{-\frac{\pi}{8}}^{\frac{\pi}{8}}$$

$$= \frac{1}{2}\left[\operatorname{erf}\left[\frac{0.3827\ z_I - 0.9239\ z_Q}{\sqrt{N_t}}\right] - \operatorname{erf}\left[\frac{-0.3827\ z_I - 0.9239\ z_Q}{\sqrt{N_t}}\right]\right] \qquad \text{(C–11)}$$

Substituting (C–1) into (C–11), and perform the outer integration, we have

$$P_c = \frac{1}{2\pi}\int_0^{2\pi}\int_{-\frac{\pi}{8}}^{\frac{\pi}{8}}\int_0^{\infty} p(r,\theta,\theta_j)\, dr\, d\theta\, d\theta_j$$

$$\cong \frac{1}{4\pi}\int_0^{2\pi}\left[\operatorname{erf}\left[\frac{0.3827\ (\sqrt{S}\cos\theta_j - \sqrt{S}\sin\theta_j) - 0.9239\ (\sqrt{S}\sin\theta_j + \sqrt{J}\cos\theta_j)}{\sqrt{N_t}}\right]\right.$$

$$\left. - \operatorname{erf}\left[\frac{-\ 0.3827\ (\sqrt{S}\cos\theta_j - \sqrt{J}\sin\theta_j) - 0.9239\ (\sqrt{S}\sin\theta_j + \sqrt{J}\cos\theta_j)}{\sqrt{N_t}}\right]\right] d\theta_j \qquad \text{(C–12)}$$

There is no close form solution for the last integral. The integration must be evaluated numerically.

The symbol error rate is given by

$$P_s = 1 - P_c \qquad \text{(C–13)}$$

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This report describes a computer software package that was developed for predicting the error rate of a general HF communication system in a noisy and hostile environment. The original software was designed to facilitate the establishment of a new STANAG (Standard NATO Agreement) for radio communications in the HF band. The program estimates the bit error rate for a variety of system configurations, operational parameters, jammer characteristics and ground wave propagation media, as selected by the user. Sky wave propagation is not considered. This package includes M-ary and PSK (M = 2, 4, 8) signals, CCIR background noise and measured European interference environments. Frequency hopping can be used by the transmitter to evade jamming. The jammer may, in turn, use either follower or partial-band jamming signals to counter the evasion. Estimation of error rate is based on analytical solutions rather than simulations. The cases for M-ary FSK with noise/tone jamming, and 8-ary PSK with tone jamming were analyzed and closed form solutions were obtained. The program was made flexible enough to allow one to predict and compare the performances of existing and proposed HF communication systems for a variety of operational environments.

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